Optimization of Solar-Powered and Continually Sustained Flight in Unmanned Aerial Vehicles for Variable Mission Criteria

Feasibility analysis using Mathematical optimization of solar-powered aircraft using first principles for different mission cases.

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Optimization?

Variable Mission Criteria?

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Why?

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- Air Travel and Freight
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Methodology

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Schools of Focus

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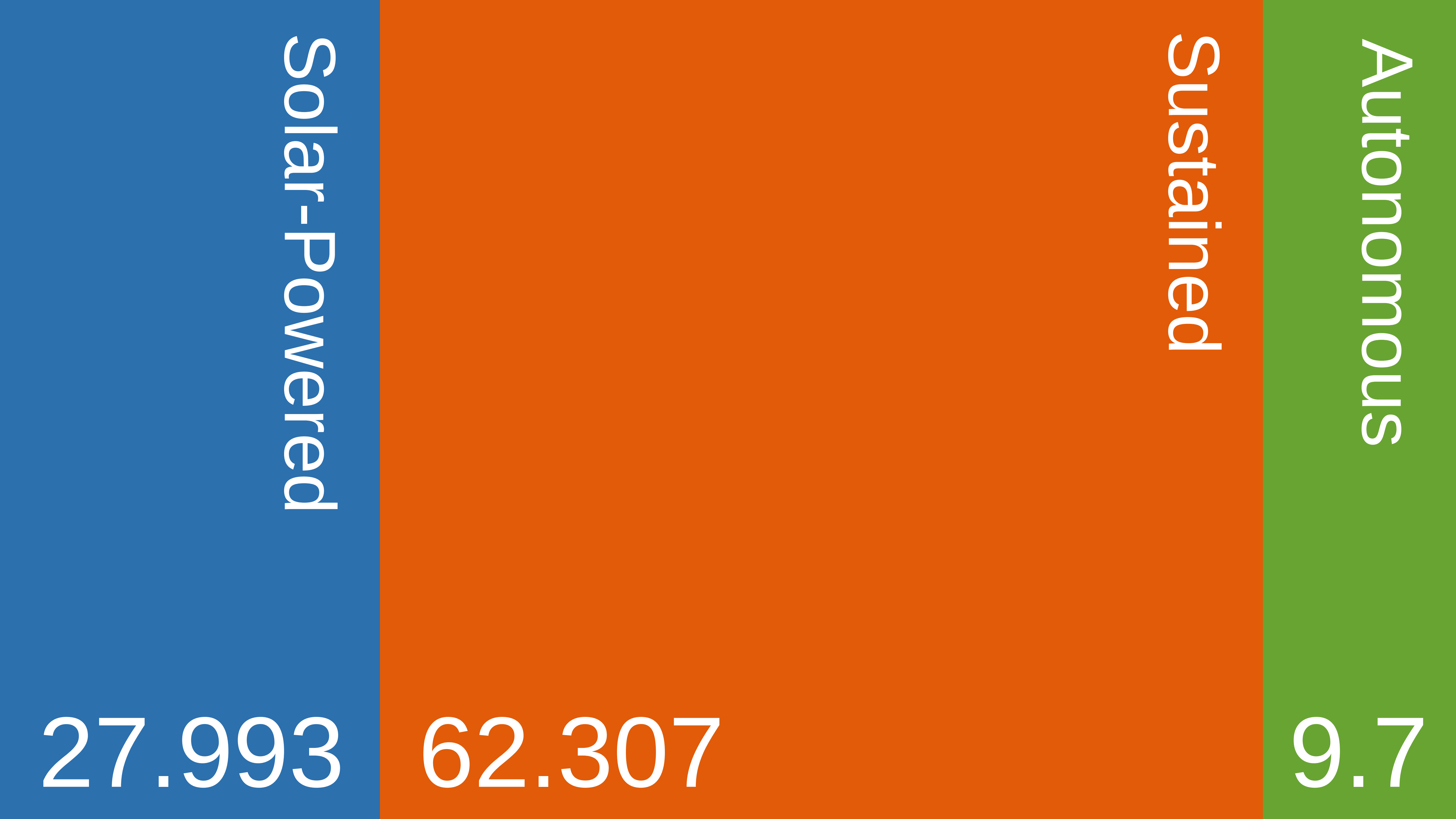
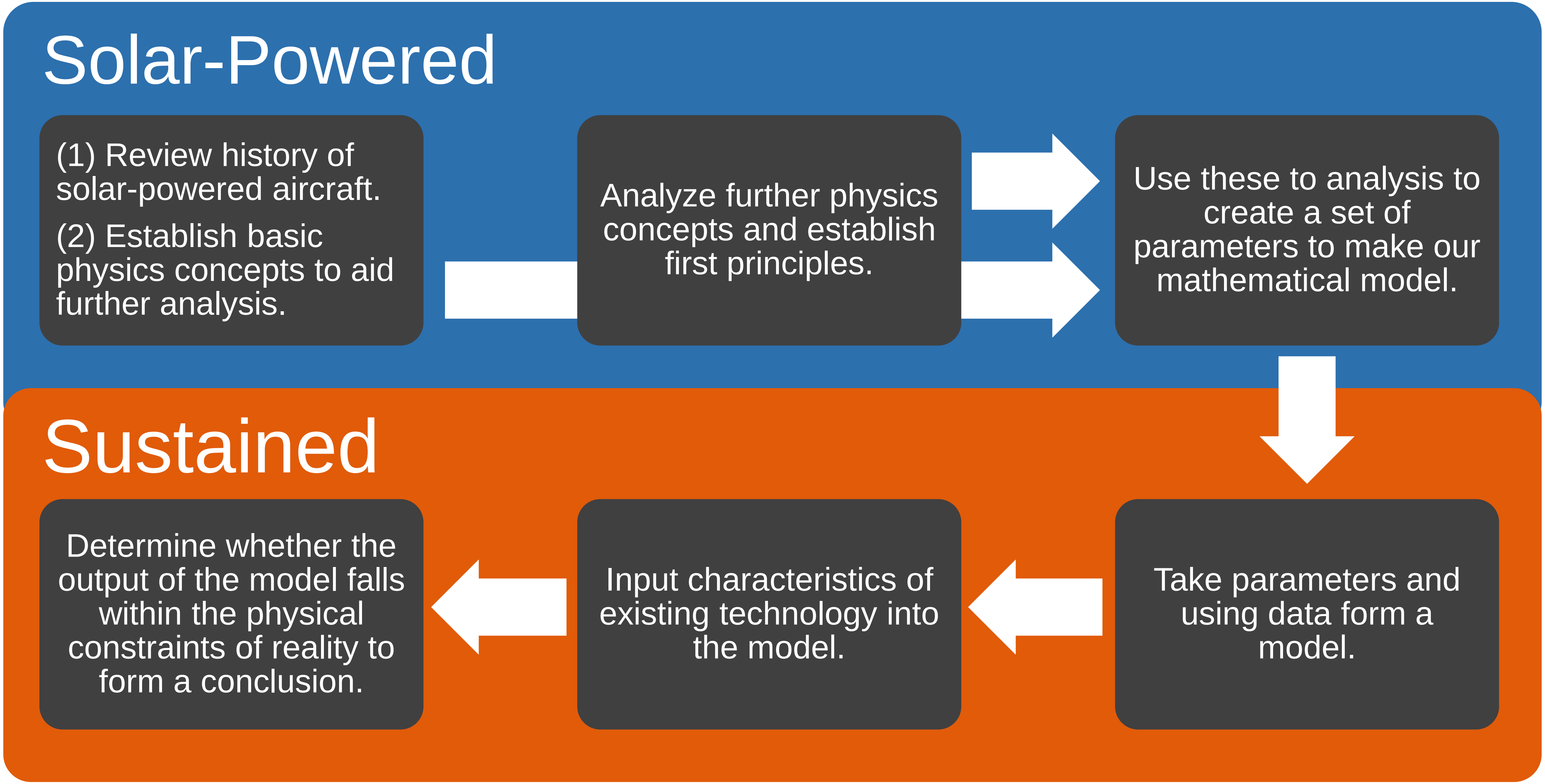

Solar-Powered
27.993
Sustained
62.307
Autonomous
9.7


Solar-Powered
(1) Review history of solar-powered aircraft.
(2) Establish basic physics concepts to aid further analysis.
Analyze further physics concepts and establish first principles.
Use these to analysis to create a set of parameters to make our mathematical model.
Sustained
Take parameters and using data form a model.
Input characteristics of existing technology into the model.
Determine whether the output of the model falls within the physical constraints of reality to form a conclusion.

Interconnectedness?

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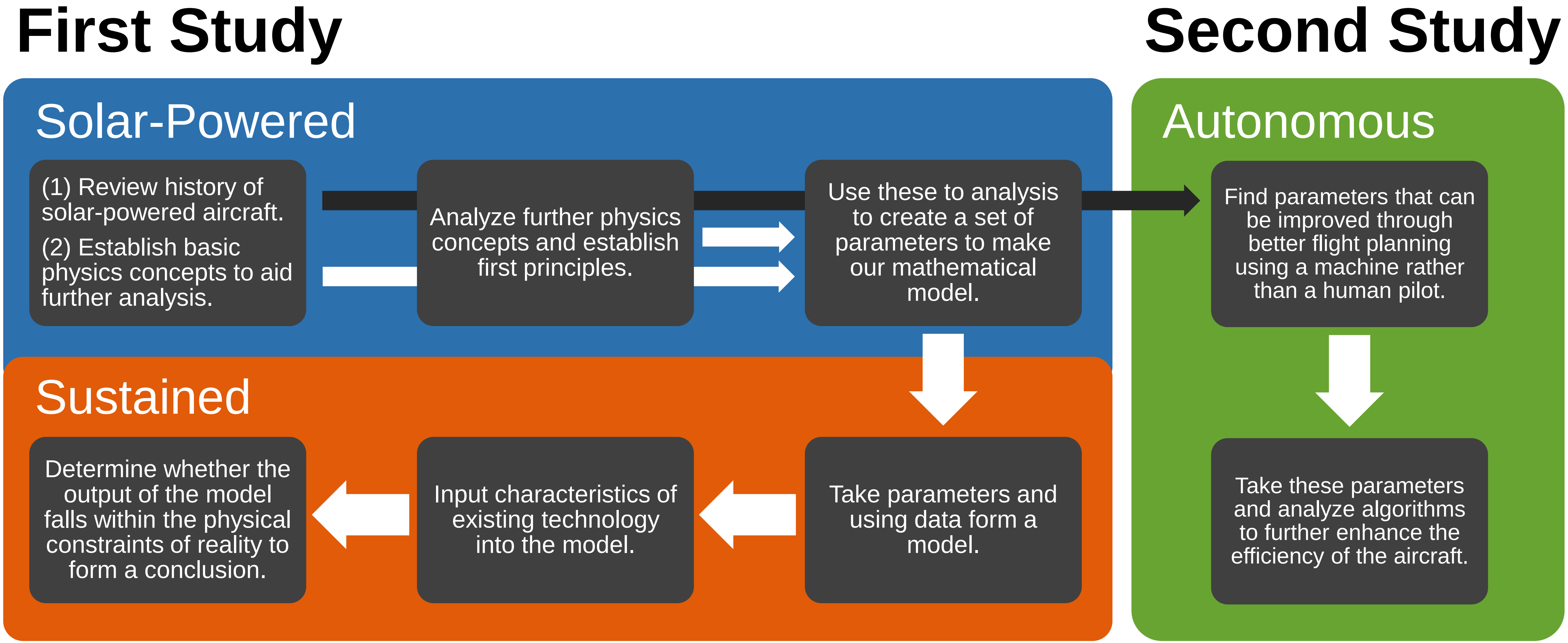

First Study
Second Study
Solar-Powered
(1) Review history of solar-powered aircraft.
(2) Establish basic physics concepts to aid further analysis.
Analyze further physics concepts and establish first principles.
Use these to analysis to create a set of parameters to make our mathematical model.
Autonomous
Find parameters that can be improved through better flight planning using a machine rather than a human pilot.
Sustained
Determine whether the output of the model falls within the physical constraints of reality to form a conclusion.
Input characteristics of existing technology into the model.
Take parameters and using data form a model.
Take these parameters and analyze algorithms to further enhance the efficiency of the aircraft.

The Solar-powered Focus

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Chapter

01

Chapter 1: History of Solar-powered Flight

1.1 Early History of Electric Flight and Photovoltaics

The utilization of electric power for the propulsion of flight vehicles is not a recent development. The first instance of this was in 1884 with the hydrogen-filled dirigible France, emerged victorious in a 10 km race around Villacoulbay and Medon. During this period, the electric system was deemed superior to the steam engine. However, with the advent of gasoline engines, research on electrical propulsion for air vehicles was abandoned, and the field remained dormant for 73 years. [13]

On the 30th of June 1957, Colonel H. J. Taplin of the United Kingdom conducted the first officially recorded electric-powered radio-controlled flight with his model "Radio Queen," which utilized a permanent-magnet motor and a silver-zinc battery. Unfortunately, he did not continue with these experiments, but subsequent advancements in the field were made by Fred Militky, who achieved a successful flight with an uncontrolled model in October 1957. Since then, electric flight has continuously evolved with constant improvements in the fields of motors and batteries. [12, 14]

Three years prior to Taplin and Militky's experiments, in 1954, photovoltaic technology was developed at Bell Telephone Laboratories. Daryl Chapin, Calvin Fuller, and Gerald Pearson created the first silicon photovoltaic cell capable of converting enough of the sun's energy into power to run everyday electrical equipment. Initially, the efficiency was at 4%, but it rapidly improved to 11%. [12, 15]

It took two more decades after this to witness the utilization of solar technology for the propulsion of electric model airplanes. [12]

1.2 Introduction

1.2.1 Objectives

The Wright brothers made the first successful powered, controlled and sustained aircraft flight on December 17, 1903. Only a decade later, at the start of World War I, heavier-than-air powered aircraft had become practical for artillery spotting, reconnaissance, and attacks against ground positions. During the Second World War primitive jet technology was developed leading to aircraft that could ferry passengers and freight from place to place in mere hours leading us into a "jet-age". After a sustained period of technological development, we are approaching a stagnation in aviation where we focus on the perfection of fossil-fuel based aircraft rather than the development of solar-powered aircraft that may prove to be the future of air travel, freight carrying, search-and-rescue operations, industrial inspection, agricultural irrigation, telecommunications, internet serviceability in remote regions, delivery of medical supplies, etc.

A theoretically infinite flight-time for solar-powered Unmanned Aerial Vehicles (UAVs) is a lucrative avenue of aircraft development if followed. It would enable a huge range of mission and applications to be rolled out universally where it was previously too economically expensive.

This dissertation therefore assesses whether it is possible to achieve a solar-power based singularity wherein an aircraft is able to fly perpetually and autonomously with today's technology, which in the coming years may perhaps again revolutionize the aerospace industry as once before.

1.2.3 Importance

Sustained solar flight has shown great promise over the last 40 years of continual development, however the singularity in which sustained practical flight which may easily be deployable, affordable and reliable has not come into fruition.

Widespread use of such a technology can completely revolutionize the world in which we live where aircraft can stay in the sky for months –perhaps even years– at a time completing important tasks in the functioning of our society which otherwise would be done using polluting conventional aircraft and UAVs.

1.2.4 Motivation

I have developed a great interest in "practical sustainability" in which our industry and basic necessities are made to be sustainable sustainably, meaning that changes are made in such areas where they result in sustainability without compromising on their original capacity. As such; I have produced a prototype "water catching" system in which water vapour can be "caught" in arid mountain-scapes where ground water and rainwater is inaccessible but low lying fog and clouds carrying a large amount of water can be taped into as part of my GCSE Design and Technology NEA; and a prototype solar powered desalination system which can take water with impurities and distil it using a lens that focuses the sun's energy to purify said water.

This EPQ acts as an extension of my interest in finding practical solutions to the requirement of sustainability in our industrial processes without compromising on scale and practicability.

1.2.5 Scope and Goal

The scope of this paper will be limited to:

(1) History of solar-craft leading up to the current position of solar aircraft technology
(2) Relevant explanation of theory so that context analysis is established regarding:
  a. Conventional Flight Technologies (mechanics of flight)
  b. Solar-powered Flight (the electronics of solar-powered flight aircraft)
  c. Autonomous Flight Systems
(3) Discussion around the optimization and choice-weighing through multiple parameters established in the first section of:
  a. Mechanical Design of airframe
  b. Electronic Components regarding solar-flight
  c. Autonomous Algorithms and use of electronic devices
(4) Conclusion of question posed in this dissertation through:
  a. Separate Conclusions for:
    i. Solar-powered
    ii. Sustained
    iii. Autonomous
  b. A "Grand Conclusion" outlining a summary of the above conclusion
  c. A possible prototype using existing or near-future technologies to exemplify a possible solar-aircraft

The overall objective of this dissertation is to examine whether it is feasible for unmanned aircraft called UAVs (unmanned aerial vehicles) to achieve the following with current day technologies:

(1) Be able to be practically solar-powered in the sense it is feasible and affordable
(2) Be able to achieve theoretical infinite flight time in the sense it is feasible and affordable
(3) Be able to adapt autonomously to allow for complex missions and designations in the sense that it is feasible and affordable

History of Solar Flight July 2008

Nr.	Name	Year	Designer, Manufacturer	Source	Wing & Fuselage: Wingspan [m]	Mean Chord [m]	Length [m]	Wing Area [m2]	Aspect Ratio []	Weight: Empty Weight [kg]	Total Weight with Pilot/Payload [kg]
1	Sunrise	1974	R.J. Boucher from Astro Flight, USA	Book "Solar Modellflug", page 9	9.75	0.86	4.38	8.36	11.4	12.25	
2	Sunrise II	1975	R.J. Boucher from Astro Flight, USA	Book "Solar Modellflug", page 9	9.75	0.86	4.38	8.36	11.4	10.21	
3	Solaris	1976	Fred Militky, Germany	Book "Solar Modellflug", page 10	2.06	0.20		0.41	10.3	0.61	
4	Ra	1977	Prof. Dr. V. Kupciks	Book "Solar Modellflug", page 12	1.37	0.12	0.84	0.16	11.9	0.19	
5	Utopie	1977	Dr. Roland Stuck, France	Book "Solar Modellflug", page 13	2.53	0.20	1.32	0.51	12.6	0.97	
6	Solar-Student	1978	Prof. Dr. V. Kupciks	Book "Solar Modellflug", page 14	1.96	0.22	1.04	0.43	8.91	0.93	
7	Solar One	1978	David Williams and Fred To	R. J. Boucher, History Of Solar Flight, AIAA Paper 84-1429, June 1984	20.72	1.17	6.70	24.15	17.8	104.32	?
8	Solar-X4	1979	H. Schenk	Book "Solar Modellflug", page 15	2.50	0.17	1.13	0.42	14.8	0.85	
9	Solar Silberfuchs	1979	Günter Rochelt	Book "Solar Modellflug", page 17	4.00	0.25	1.52	1.00	16	2.10	
10	Solar Riser	1979	Larry Mauro	http://www.airventuremuseum.org/collection/aircraft/UFM-Mauro Solar Riser.asp	9.14	1.04	2.44	9.52	8.78	55.8	124.7
11	Solar-HB79	1980	Helmut Bruss	Book "Solar Modellflug", page 16	2.80	0.24	1.45	0.67	11.7	1.51	
12	Solair I	1980	Günter Rochelt	http://www.delago.de/solair/ESol2-7.htm	16.00	1.38	5.40	22.00	14	120.00	200.0
13	Gossamer Penguin	1980	Dr. Paul B. MacCready from Aerovironment	http://www1.nasa.gov/centers/dryden/pdf/120308main_FS-054-DFRC.pdf	21.64	2.63		57.00	8.22	30.84	67.7
14	Solar-HB80	1981	Helmut Bruss	Book "Solar Modellflug", page 19	2.84	0.23	1.48	0.65	12.5	1.72	
15	Solar Challenger	1981	Dr. Paul B. MacCready from Aerovironment	http://www1.nasa.gov/centers/dryden/pdf/120308main_FS-054-DFRC.pdf	14.80	1.48	9.22	21.83	9	99.79	153.0
16	Solus Solar	1984	Helmut Bruss, F.W. Biesterfeld	Book "Solar Modellflug", page 20	3.20	0.29	0.88	0.93	11	2.20	
17	Poly	1986	Helmut Bruss	Book "Solar Modellflug", page 21	3.24	0.29	0.88	0.97	10.8	2.48	
18	Combi	1987	Peter Hartwig	Book "Solar Modellflug", page 23	2.96	0.26	0.85	0.77	11.4	2.29	
19	Solariane	1987	Franz Weissgerber, Ernst Schöberl	Book "Solar Modellflug", page 24	3.08	0.28	1.72	0.85	11.2	1.80	
20	Helios (model)	1989	Erich Töpfer	Book "Solar Modellflug", page 26	2.14	0.18		0.39	11.8	1.40	
21	Bloch	1989	Edwin Bloch	Book "Solar Modellflug", page 26	2.90	0.24		0.70	12	1.25	
22	Grosholz	1989	Rainer Grosholz	Book "Solar Modellflug", page 26	3.07	0.19		0.60	15.8	1.85	
23	Combi 2	1989	Helmut Bruss	Book "Solar Modellflug", page 28	2.95	0.28	1.54	0.77	11.3	1.70	
24	Ikaros	1989	Franz Weissgerber	Book "Solar Modellflug", page 26	2.50	0.23		0.58	10.8	1.80	
25	Bleher	1989	Wolfgang Bleher	Book "Solar Modellflug", page 26	2.00	0.24		0.49	8.18	1.37	
26	Romarino	1989	Urs Schaller	Book "Solar Modellflug", page 26	2.00	0.20		0.40	10	1.80	
27	Sol-e-moi	1989	Alfred Hitzler	Book "Solar Modellflug", page 26	3.00	0.17		0.50	18	2.10	
28	Wolf	1989	Josef Wolf	Book "Solar Modellflug", page 26	3.00	0.21		0.63	14.3	1.60	
29	WS-Solar	1989	Wener Schleidt	Book "Solar Modellflug", page 26	2.50	0.22		0.55	11.3	1.55	
30	Ariane Ultra	1989	Franz Weissgerber	Book "Solar Modellflug", page 26	1.98	0.21	1.14	0.41	11	3.02	
31	Solar Voyager	1990	Volker Klein	Deutsche Museum, Flugwerft Schleißheim	3.20	0.25		0.79	13	1.30	
32	Mardini	1990	Hans-Jakob Sommerauer	Book "Solar Modellflug", page 29	2.40	0.25		0.60	9.6	2.50	
33	Sollisolar	1990	Edwin Bloch	Book "Solar Modellflug", page 29	2.98	0.23		0.69	12.9	1.23	
34	PB 26-FL	1990	Marco Buholzer	Book "Solar Modellflug", page 29	2.60	0.22		0.58	11.8	2.30	
35	Solarbaby	1990	Werner Dettweiler	Book "Solar Modellflug", page 29 & 106	1.70	0.16		0.28	10.4	1.25	
36	Bleher	1990	Wolfgang Bleher	Book "Solar Modellflug", page 29	2.00	0.22		0.44	9.03	1.55	
37	Uccello	1990	Josef Kapfer	Book "Solar Modellflug", page 29	2.70	0.23		0.63	11.5	1.90	
38	Sole Florentino	1990	Franz Weissgerber	Book "Solar Modellflug", page 29	2.50	0.17		0.43	14.6	1.20	
39	Soli	1990	Ernst Schöberl	Book "Solar Modellflug", page 29	2.08	0.18		0.38	11.5	1.50	
40	Playboy	1990	Thomas Bley	Book "Solar Modellflug", page 29	2.40	0.19		0.45	12.8	1.35	
41	WS12 (then WS16)	1990	Dr. Wolfgang Schaeper	Book "Solar Modellflug", page 29	2.50	0.16	1.10	0.41	15.2	0.84	
42	Solar Flyer	1990	Peter Hartwig	Book "Solar Modellflug", page 104	2.64	0.23	1.48	0.61	11.5	1.60	
43	Blue Chip	1990	Hans W. Müller	Book "Solar Modellflug", page 108	2.20	0.23	1.25	0.50	9.66	0.75	
44	Solarmax	1990	Erich Töpfer	Book "Solar Modellflug", page 110	3.48	0.30	1.59	1.04	11.6	2.54	
45	Sollisolar 89-2	1990	Edwin Bloch	Book "Solar Modellflug", page 111	2.98	0.23	1.34	0.68	13.1	1.24	
46	Phönix	1990	Jens Stattler	Book "Solar Modellflug", page 112	2.62	0.21	1.29	0.56	12.2	1.18	
47	Sunseeker	1990	Eric Raymond	http://www.solar-flight.com/sslink.html						?	?
48	Solar UHU	1991	Graupner (Ref. 4274)	http://members.ebay.co.uk/ws/eBayISAPI.dll?ViewUserPage&userid=airxav	2.30	0.23	1.20	0.53	10	1.45	
49	Blue-Wing	1991	Norbert Ladenburger, Germany	"Aufwind", Issue 2, 1992	2.34	0.18	1.05	0.42	13	0.75	
50	Solar Schilti 1	1991	Jean-Pierre Schiltknecht	FMT Sonderdruck aus FMT 1-4/1992	1.74	0.19	1.16	0.34	9	0.70	
51	Solar Schilti 2	1991	Jean-Pierre Schiltknecht	RC Modely, Issue 4, 1997	1.99	0.18	1.05	0.36	11.1	0.82	
52	Silizi Solar	1991	Horst Groner	Flug- und Modelltechnik 423-4/91	2.25	0.21	1.30	0.47	10.7	1.08	
53	Solix	1991	Ernst Schöberl	Flug- und Modelltechnik 443-12/92	2.37	0.20	1.30	0.48	11.8	1.05	
54	Solar mini challenger	1992	Astro Flight	http://www.bekkoame.ne.jp/~sakazaki/fwind/list-e.html	1.55	0.18		0.28	8.5	0.94	
55	Rival-8 Solaris	1992	Palo Lishak, Slovakia	http://www.rcgroups.com/forums/showthread.php?t=291266	1.96	0.22	1.13	0.43	8.91	0.66	
56	Pathfinder	1994	AeroVironment, NASA	http://www1.nasa.gov/centers/dryden/pdf/120308main_FS-054-DFRC.pdf	29.50	2.40	3.60	70.80	12.3	207.00	252.0
57	MikroSol	1995	Sieghard Dienlin	http://home.main-rheiner.de/sieghard.dienlin/	1.13					0.19	
58	Solair II	1996	Günter Rochelt	http://www.delago.de/solair/ESol2-7.htm	20.00	0.86	6.12	17.00	23.5	140.0	230.0
59	Icare II	1996	UNI Stuttgart, Rudolf Voit-Nitschmann	http://www.uni-stuttgart.de/wechselwirkungen/ww2001/nitschmann.pdf	25.00	1.03	7.70	25.70	24.3	270.00	360.0
60	Lo 120 Solar	1996	Hugo Post	Book "Fliegen mit Licht", page 123	15.46	1.03		16.00	14.9	?	
61	Solarflugzeug	1996	Uwe Heinemann	Book "Fliegen mit Licht", page 123	18.00	1.50		27.00	12	190.00	280.0
62	O sole mio	1996	Dr. Antonio Bubbico	http://www.uni-stuttgart.de/wechselwirkungen/ww2001/nitschmann.pdf	20.00	1.23		24.50	16.3	130.00	220.0
63	Solar Solitude	1996	Dave Beck	http://personalpages.tds.net/~dbeck/	2.70	0.20		0.55	13.3	2.00	
64	NanoSol	1996	Sieghard Dienlin	http://home.main-rheiner.de/sieghard.dienlin/	1.11					0.16	
65	Centurion	1997	AeroVironment, NASA	http://www1.nasa.gov/centers/dryden/pdf/120308main_FS-054-DFRC.pdf	61.80	2.40	3.60	148.32	25.8	533.00	862.0
66	Trosollmuffel	1997	Bernd Bossmann	http://www.delago.de/ariane/Elntmod.htm	2.50	0.25		0.62	10.1	1.14	
67	Global Flyer	1997	Helmut Bruss	FMT Magazine, Issue 7, 1998	2.50	0.23	1.20	0.57	11	1.04	
68	Pathfinder Plus	1998	AeroVironment, NASA	http://www1.nasa.gov/centers/dryden/pdf/120308main_FS-054-DFRC.pdf	36.30	2.40	3.60	87.12	15.1	247.50	315.0
69	Solar Excel	1998	Wolfgang Schaeper	http://li-windpower.homelinux.net/SunSailor/cf2000.pdf	2.10	0.16	1.02	0.35	12.8	0.72	
70	Solitair	1998	DLR Institute of Flight Systems	http://www.dlr.de/ft/desktopdefault.aspx/tabid-1358/1891_read-3339/	5.20					?	
71	PicoSol	1998	Sieghard Dienlin	http://home.main-rheiner.de/sieghard.dienlin/	0.99					0.13	
72	LFMA	1998	Louis Fourdan, Michel Astier, France	Louis Fourdan	1.90	0.25		0.47	7.76	1.20	
73	Helios	1999	AeroVironment, NASA	http://www1.nasa.gov/centers/dryden/pdf/120308main_FS-054-DFRC.pdf	75.30	2.48	3.60	186.60	30.4	600.00	930.0
74	Sunrazor (Sunriser)	2000	Patrick Berry	The Sunriser - A Design Study in Solar Powered Flight.pdf	2.70	0.30		0.81	9.06	1.10	
75	Goldcap 2	2001	Helmut Bruss	http://www.dienlin.de/sieghard/ModellTechnik/Bildergalerie.html						?	
76	Solarus	2001	Jonas Romblad	http://www.rcgroups.com/forums/showthread.php?t=136218	2.30	0.19		0.44	12	0.48	
77	FlyG	2002	Royal Institute of Technology, KTH	http://130.237.36.221/cdio/old_projects/sap/index.html	6.00	0.60	2.70	3.60	10	10.00	
78	Solar Pleaser	2003	Unknown	http://www.rcgroups.com/forums/showthread.php?t=88868	1.04	0.15	1.01	0.15	7	0.25	
79	No Name	2003	Matt Keennon	http://aero.stanford.edu/Reports/AIAA20040001b.pdf	0.14	0.015	0.12	0.00	9.33	0.0017	
80	Solar Splinter	2003	Paul Breed	http://www.rasdoc.com/splinter/	4.27	0.35	2.13	1.50	12.2	4.50	
81	Sol-Mite	2004	Ralph Bradley	http://www.parmodels.com/ralphs_models.htm	0.81	0.12		0.10	6.5	0.13	
82	Sky-Sailor	2005	André Noth, Walter Engel, Roland Siegwart, [	http://sky-sailor.epfl.ch	3.20	0.24	1.82	0.78	13.2	2.50	
83	Zephyr	2005	QinetiQ	http://www.qinetiq.com	18.00	1.55		27.90	11.6	30.00	
84	Solong	2005	Alan Cocconi from AcPropulsion	http://www.acpropulsion.com	4.75	0.32		1.50	15	12.60	
85	NanSun	2006	Troy Tegeder	http://contentdm.lib.byu.edu/ETD/image/etd1723.pdf	3.20	0.40	2.60	1.28	8	4.10	
86	Howie Mark	2006	Louis Dube, Joshua Alves, Corey Ohnstad	University of Nevada	2.43	0.20		0.49	12.2	0.45	
87	SunSailor	2006	Technion IIT, Haifa, Israel	http://li-windpower.saymoo.org/SunSailor.html	4.20	0.32	2.20	1.35	13.1	3.60	
88	Aphelion	2006	Carl Engel and Adam Woodworth from MIT	http://www.rcgroups.com/forums/showthread.php?t=572000	3.13	0.22		0.70	14	?	
89	2.765 g Solar MAV	2007	Brian Daniels	http://www.rcgroups.com/forums/showthread.php?t=731011	0.14	0.04	0.15	0.0057	3.41	0.0022	
90	SolFly	2007	Helmut Schweig	http://www.rcgroups.com/forums/showthread.php?t=691420	0.07					<0.001	
91	Micro-Mite	2007	Ralph Bradley	http://www.parmodels.com/ralphs_models.htm	0.20	0.05		0.01	4	0.0095	
92	Sun-Surfer I	2007	Niels Diepeveen, ETH Zürich	http://sky-sailor.epfl.ch/publications.htm	0.77	0.00	0.73	0.07	8.5	0.12	
93	Sun-Surfer II	2007	Beat Fuchs, ETH Zürich	http://sky-sailor.epfl.ch/publications.htm	0.78	0.11	0.74	0.09	7.03	0.188	

Contact **Any comment, advice or additionnal record is welcome**

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Chapter 1: The Principles of Controlled Flight

Chapter 01

1.1 Introduction

To begin weighing the suitability of different electronic technologies, the context of our analysis must first be stated, as such we first must briefly go into detail regarding the way mechanical components work on conventional aircraft.

To begin analysing whether it is possible to have a practical and feasible solar aircraft that can fly for a theoretically infinite period of time, a mathematical model must be drawn up. To draw this mathematical model the underlying first principles physics must be established to allow for the connection of seemingly unrelated electrical and mechanical real-world parameters such as coefficient of drag, Oswald efficiency factor of a wing, battery charge and discharge efficiencies, etc.

Only the essential theory required to optimize and deduce whether the proposition of this dissertation is feasible will be analysed.

1.2 The Basic Principles of Flight

1.2.1 The Forces Involved in Level Flight

All aircraft must be designed with the following forces in mind to ensure the craft has optimum flight characteristics: thrust from the engine F_{Thrust}, the lift from the wings of the aircraft F_{Lift}, the weight of the aircraft F_{Weight}, and lastly the drag of the aircraft F_{Drag}. Controlling these values will allow the aircraft to at least become airborne before we need to implement control.

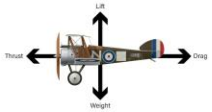


Figure [1.2].1: Forces acting on an aircraft during level flight featuring the Sopwith Camel. This is only a rough simplification as the centre of mass of the aircraft is close to the bottom wing of the craft and here forces are acting through the visual centre not the centre mass, the next diagram remedies this problem.

Especially for the use case of solar-powered aircraft the parameters that most directly affect F_{Drag} and F_{Weight} must be controlled as much as possible with the remaining two factors falling below them in priority.

The following is during level flight in optimal conditions such as sea-level pressure, air temperature in the range of 10°C to 50°C. The airflow due the relative velocity of the aircraft to the air creates the force of F_{Lift} and F_{Drag}, both which are balanced by F_{Weight} and F_{Thrust}. F_{Lift} is a result of air flowing over the wings creating a pressure difference and is a sort of "manufactured force" in the sense that it a result of the designers of the aircraft adding wings, it allows the aircraft to overcome the F_{Weight} thus allowing us to take flight or remain at a constant altitude during level flight. F_{Drag} is a force due to the inefficiencies in our aircraft's design, F_{Drag} can never equal to zero as the drag coefficient (discussed further) is always greater than zero. F_{Thrust} is, in short, a result of the propeller creating a pressure difference and thus a force, this force must exceed F_{Drag} for the aircraft to accelerate, must be the same as F_{Drag} for the aircraft to remain at a constant velocity, and must be less that F_{Drag} for the aircraft to decelerate.

1.2.2 Balancing the Forces in Flight

We can split the 4 forces into the x-plane and y-plane and from there use newton's first law to simple calculate the force required for the aircraft to accelerate, remain at a constant velocity, decelerate in both axis. As represented on a free-body diagram in figure [1.2].1, [3]:

$$\Sigma F_x = ma \qquad \text{Equation [1.2].01}$$

$$\Longrightarrow \quad F_{Thrust} - F_{Drag} = ma \qquad \text{Equation [1.2].02}$$

$$\Sigma F_y = ma \qquad \text{Equation [1.2].03}$$

$$\Longrightarrow \quad F_{Lift} - F_{Weight} = ma \qquad \text{Equation [1.2].04}$$

Variable	Description	
F_x	Forces in the x axis	Symbol [1.2].01
F_y	Forces in the y axis	Symbol [1.2].02

It should be noted that we subtract place both F_{Drag} and F_{Weight} as being subtracted from their respective forces as we are taking the upwards plan and the leftwards directions as positive as it would be must intuitive as that is both the top and the front of the aircraft.

1.3 Controlling flight

1.3.1 The Importance of Control

For the solar aircraft to be able to fly theoretically infinitely, the craft first must be able to be controlled – autonomously or not, there is a need for control surfaces.

1.3.2 The Control Surfaces Required

Unpowered gliders have existed long before the Wright Flyer, such as George Cayley's full-scale glider published as part of his three-part treatise where it included the world's first (known) manned flight in 1853. [17] Powered aircraft have also existed long before the Wright Flyer such as the first unmanned powered aircraft in 1848 built by John Stringfellow. [19] There have also been manned powered flights such as Ader Avion III built by Clément Ader which achieved "hops" whereby it would take off and then haphazardly land back, flying a few meters. [18] All of these flights did not succeed like the Wright Flyer did as a result of not having one thing: control.

The Wright Flyer succeeded due to the ability to control itself in flight, this allowed it not to crash and sustain flight. The Wright brothers had invented three axis flight [2] allowing their aircraft to succeed.

For a solar-powered it must be able to be controlled for it to be able to sustain flight. To do this, the craft must use the three axes of control: roll, pitch, and yaw. [20] Small wings called control surfaces are moved into the flow of air to create a force against the aircraft and thus cause it to manoeuvre.

The diagrams below show the axes of movement and their relevant control surfaces that allow such movement.

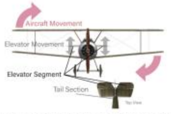


Figure [1.3].1: Axis of roll, control surfaces called ailerons cause this motion.

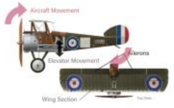


Figure [1.3].2: Axis of pitch, control surfaces called elevators cause this motion.

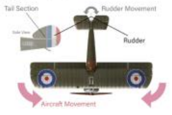


Figure [1.3].3: Axis of yaw, a control surface called the rudder causes this motion.

1.4 Aerodynamics of wings

1.4.1 The Problem

To successfully become airborne, designers must consider the aerodynamics of the wing carefully in the sense that the wing must create lift whilst not creating too much drag and ensuring suitable flight characteristics depending on the average velocity of the craft. Suitable flight characteristic during stalls and high winds should also be taken into consideration for the development of a low-speed solar UAV.

1.4.2 The Forces on an Aerofoil

The figure [1.4].1 shows a cross section of a wing in the optimum condition of laminar flow at a constant velocity of v. The relative airflow over the wing creates a difference in pressure the top of the wing and the bottom wing that once resolved create the two forces of F_{Drag} and F_{Lift}

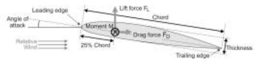


Figure [1.4].1: Cross-section of an aircraft's aerofoil. The cross encased in a circle represents the centre of mass of the wing and that is the place where forces act through, F_{Weight} has been omitted to reduce complexity as we are analysing the wing only and F_{Weight} considers the entire weight of the aircraft.

The forces of F_{Drag} and F_{Lift} can be calculated using the following formulae:

$$F_D = C_D \frac{\rho}{2} A_W v^2 \qquad \text{Equation [1.4].01}$$

$$F_L = C_L \frac{\rho}{2} A_W v^2 \qquad \text{Equation [1.4].02}$$

Variable	Description	
F_D	Force due to drag, previously F_{Drag}, henceforth F_D.	Symbol [1.4].01
C_D	Coefficient of Drag	Symbol [1.4].02
F_L	Force due to lift, previously F_{Lift}, henceforth F_L.	Symbol [1.4].03
C_L	Coefficient of Lift	Symbol [1.4].04
ρ	Density of air	Symbol [1.4].05
A_W	Area of the wing	Symbol [1.4].06
v	Speed of aerofoil relative to the air (Relative airspeed)	Symbol [1.4].07

1.4.3 The Importance of the Optimization of the Glide Ratio

To ensure that the aircraft is highly performant in the sense that we need to use very little energy in our solar craft to gain a large amount of altitude as we can generate a lot of lift without the expense of an immense increase in drag. With this in mid, we must maximize and optimize the ratio between ${}^{F_L}/_{F_D}$ and consequently the ratio between ${}^{C_L}/_{C_D}$ as $F_L \propto C_L$ and $F_D \propto C_D$. To achieve this, we must try to maximize C_L and minimize C_D while finding the most optimum ratio as given in the figure [2.4].2 and the subsequent analysis.

$${}^{C_L}/_{C_D} = \text{Glide Coefficient} \qquad \text{Equation [1.4].03}$$

1.4.4 The Factors Affecting the Glide Ratio

In both equations [1.4].1 and [1.4].2, the C_D and the C_L depend greatly on the following: the angle of attack of the aerofoil, the aerofoil shape itself, and the Reynolds number which in essence is the viscosity of the air flowing past the wing. [5]

1.4.5 The Reynolds Number and its Effect on the Glide Ratio

We can use the formula to determine the Reynolds number R_e:

$$R_e = \frac{\rho v c}{\mu}$$

$$\Longrightarrow \quad R_e = \frac{vc}{\psi} \qquad \text{Equation [1.4].04}$$

$$\psi = \frac{\mu}{\rho}$$

$$\Longrightarrow \quad \frac{1}{\psi} = \frac{\rho}{\mu} \qquad \text{Equation [1.4].05}$$

Variable	Description	
c	Wing chord	Symbol [1.4].08
μ	Bulk viscosity or Dynamic viscosity	Symbol [1.4].09
ψ	Kinematic Viscosity	Symbol [1.4].10

In the Reynolds number equation, the kinematic viscosity of air is given by dividing the bulk/dynamic viscosity by the density of air. The discussion of the meaning of bulk/dynamic viscosity and kinematic viscosity is not essential to our optimization. [4]

1.4.6 The Effect of the Angle Of Attack on the Glide Ratio

Going back, C_D and C_L are both affected by Reynolds number which has been mentioned, the aerofoil shape will be mentioned in further chapter when optimization of the wing will be analysed for an optimum solar craft, and now the relation between angle of attack and C_D and C_L shall be mentioned.

As we increase the angle of attack of an aerofoil, the value of C_L increases, but as this happens the separation of the airflow at the trailing edge of the aerofoil increases thus causing the turbulent airflow area behind the aerofoil to increase which thus increases the value of C_D. With this in mind, we can predict that there will be a negative coefficient quadratic parabola where the maximum point should be the optimum values so that the glide coefficient is maximized.

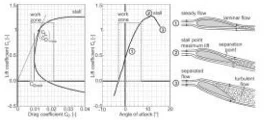


Figure [1.4].2: Drag and lift coefficients and their relation to the angle of attack.

At the stall point of the aerofoil, the lift of the aerofoil reaches its maximum but the drag is quite high – not a suitable condition. After the stall point, the behaviour is unpredictable and not easy to simulate computationally. We are still able to generally predict that drag still increases and lift remains approximately the same. Thus, logically the point of analysis should be before the stall point and is thus the point where optimization must take place.

Thus, for the generic example aerofoil the optimum angle of attack is approximately 5°.

1.4.7 Induced Drag Affecting the Drag Coefficient

So far, we have assumed the wingspan of the wing is infinite, this causes inacouracies as it removes the need to consider wing vortices at the wing tips of a wing.

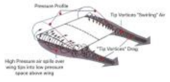


Figure [1.4].3: Wing vortices on an aerofoil. [11] (Taken form source with adjustments for clarity.)

These vortices induce an additional drag on the aircraft called induced drag, $C_{D\ Induced}$. To calculate this value, the following equation is used [6]:

$$A_r = \frac{S}{c}$$

$$\Longrightarrow \quad A_r = \frac{S^2}{Sc}$$

$$\Longrightarrow \quad A_r = \frac{S^2}{A_w} \qquad \text{Equation [1.4].06}$$

$$C_{D\ Induced} = \frac{C_L^2}{\pi e_o A_r} \qquad \text{Equation [1.4].07}$$

Variable	Description	
S	Wing span	Symbol [1.4].11
A_r	Aspect ratio	Symbol [1.4].12
$C_{D\ Induced}$	Induced Drag Coefficient	Symbol [1.4].13
e_o	Oswald Efficiency Factor	Symbol [1.4].14

The Oswald efficiency factor has a value between 0 and 1. The Lifting line theory shows that the optimum (lowest) induced drag occurs for an elliptic distribution of lift from tip to tip. The efficiency factor is equal to 1.0 for an elliptic distribution and is some value less than 1.0 for any other lift distribution such as that of a rectangular wing which is closer to 0.7. [6]

This means that optimizing our wing to an elliptical shape would allow us to increase efficiency if the placement of solar panels on the wings of the aircraft allows this.

Aircraft type	$C_{D\ Induced}$	e_o
Twin-engine piston prop	0.022 to 0.028	0.75 to 0.80
Large turboprop	0.018 to 0.024	0.80 to 0.85
General Aviation aircraft with retractable gear	0.020 to 0.030	0.75 to 0.80
General Aviation aircraft with fixed gear	0.025 to 0.040	0.65 to 0.80
Subsonic jet aircraft	0.014 to 0.020	0.75 to 0.85
Supersonic jet aircraft	0.020 to 0.040	0.60 to 0.80
Sailplane	0.012 to 0.015	0.80 to 0.90
Drones & model aircraft	0.020 to 0.045	0.75 to 0.85

Table [1.4].1: The Oswald efficiency factor of different aircraft and thereby wing shapes based on historical data. [16]

1.4.8 Parasitic Drag Affecting the Drag Coefficient

Parasitic drag is caused by the fuselage of the aircraft, the tail of the aircraft, the landing gear, sensing equipment, etc. [7] We can optimize (reduce the value of) $C_{D\ Parasitic}$ by reducing the C_D of each of the items previously mentioned such as by optimizing the aerofoil of the tail, adding an aerodynamic casing around landing gear (or having deployable landing gear, or none at all), and placing sensing equipment in line with the fuselage [7].

1.4.9 The Final Drag Coefficient Calculation

Finally, $C_{D\ Overall}$ of the aircraft can be calculated by:

$$C_{D\ Overall} = C_{D\ Induced} + C_{D\ Parasite} + C_{D\ Aerofoil} \qquad \text{Equation [1.4].08}$$

To ensure accuracy in our calculations, $C_{D\ Overall}$ is used in all equation preceding equation [1.4].4.

1.4.10 The Importance and Purpose of Optimizing Mechanics before Electronics

For the proper mathematical analysis that is to follow, the first consideration would be choosing an optimum aerofoil for low speed flight, where the glide ratio is maximized to ensure that increasing altitude requires as little energy as possible. A second point of optimization would be the angle of attack when increasing altitude.

Optimizing these two factors first would cut down on energy the most, thus increasing the chances of feasibility theoretical infinite flight as the main challenge of feasibility will lie in the electronics instead of optimization in the mechanical components which is difficult.

This conclusion is reached as electronics are easier to simulate computationally than fluids such as air over an aerofoil especially given the large range of factors such as air temperature, air pressure, aerofoil surface smoothness, relative wind speed, etc. Thus, maximizing mechanical components' efficiency first and then maximizing electronic efficiency would increase the accuracy and repeatability of the feasibility analysis.

1.5 Motor Dynamics

1.5.1 Introduction

The behaviour of DC motors with respect to their mechanical principles will be described shortly here, a discussion on the theory behind the DC motor is discussed in chapter 2.6. We shall use the following equations to optimize both the electronics and mechanical components in the analysis section of this paper.

Using the following two equations would allow us to optimize the mechanical components and propulsion group of the electronics. [32]

1.5.2 The two equations

Equations as follows [32]:

$$\begin{cases} U = r_a i + k_u \omega_{mot} \\ M_{em} = k_m i \end{cases} \qquad \text{Equation [1.5].01}$$

$$\Longrightarrow \quad \omega_{mot} = \frac{U - r_a i}{k_u} \qquad \text{Equation [1.5].02}$$

Variable	Description	Unit	
U	Terminal voltage from supply to motor		Symbol [1.5].01
r_a	Terminal resistance		Symbol [1.5].02
i	Current		Symbol [1.5].03
k_u	Voltage constant	[V⁻¹ s⁻¹ rad⁻¹]	Symbol [1.5].04
k_m	Velocity constant	[rad⁻¹ V⁻¹ s⁻¹]	Symbol [1.5].05
M_{em}	Electromagnetic moment		Symbol [1.5].06
ω_{mot}	Angular speed of motor shaft		Symbol [1.5].07

M_{em} is proportional to i, therefore once the friction moment of the motor is subtracted (due to mechanical friction, etc.), the effective torque (moment) generated by the motor for the given load can be calculated:

$$M_{mot} = M_{em} - M_{f_r} \qquad \text{Equation [1.5].03}$$

$$\Longrightarrow \quad M_{mot} = k_m i - k_m i_0$$

$$\Longrightarrow \quad M_{mot} = k_m(i - i_0) \qquad \text{Equation [1.5].04}$$

Variable	Description	Unit	
i	Current final		Symbol [1.5].08
i_0	Current initial		Symbol [1.5].09
M_{mot}	Moment (Torque) due to motor turn force		Symbol [1.5].10
M_{f_r}	Moment (Torque) due to internal mechanical friction		Symbol [1.5].11

For a fixed U, the velocity and torque generated by the motor are linearly proportional. For varying voltages, the lines in figure [1.6].2(a) are parallel with changing slope. [33]

This thus means that only the load upon the motor will hold the working point, where the working point is the intersection of the angular velocity/torque characteristic curves of the motor and the angular velocity/torque characteristic of the load.

Combing equations equation [1.5].01 and equation [1.5].02 the following is obtained:

$$M_{mot} = k_m(i - i_0)$$

$$\Longrightarrow \quad \frac{M_{mot}}{k_m} + i_0 = i$$

$$U = r_a i + k_u \omega_{mot}$$

$$\Longrightarrow \quad U = r_a\left(\frac{M_{mot}}{k_m} + i_0\right) + k_u \omega_{mot} \qquad \text{Equation [1.5].05}$$

Since we are working with DC motors the following is true if all quantities are expressed in SI units:

$$k_m = k_u$$

$$\Longrightarrow \quad M_{mot} = \frac{k_m^2}{r_a}\omega_{mot} + k_m\left(\frac{U}{r_a} - i_0\right) \qquad \text{Equation [1.5].06}$$

$$\Longrightarrow \quad \omega_{mot} = -\frac{r_a}{k_m^2}M_{mot} + \left(\frac{U - r_a i_0}{k_m}\right) \qquad \text{Equation [1.5].07}$$

The above two equations exemplify the linear dependence between the angular velocity and torque by isolating them from equation [1.5].05.

1.6 The Aerodynamics of a Propeller

1.6.1 Introduction

The propeller is a device that consists of two or more twisted aerofoils, each aerofoil is called a blade. It is mounted around a central shaft and is spun to provide propulsion due to the pressure differential behind and in front the propeller similar to that of a wing, but in this case to propel the aircraft forward through a fluid rather than providing an upthrust force to create lift through a fluid. [21]

1.6.2 Stream Tube

As given in the figure below, a streamtube is a tubular (need not be conformed to one axis, can vary in diameter and follow a curve) region of fluid surrounded by streamlines. Streamlines do not intersect meaning that same streamlines pass through a streamtube at all points along its length. [23]

1.6.3 Blade Element Theory (BET)

BET gives insight into propeller performance during rotation and under air velocity

Using such a theory, if we consider a stream tube around the propeller as the mass of air passing through the said tube or cylinder. We also assume that rate of the mass passing through the tube is constant therefore meaning to maintain the same mass per unit time, an increase in the air velocity around the propeller leads to a contraction of the stream tube passing through the plane of rotation of the blades. [23, 22]

In this theory the blade is assumed to be composed of a number of infinitesimal strips with width Δr that are connected from tip to tip. The lift and drag are estimated at the strip using the 2D aerofoil characteristics of the section. The local flow characteristics area are accounted for in terms of climb speed, inflow velocity, and angular velocity. The section lift and drag is able to be calculated and integrated over the blade span. [27]

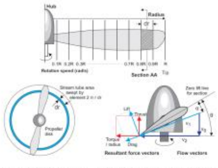


Figure [1.6].1: Blade element theory in action. [27] (Taken form source with adjustments for clarity.)

The propeller efficiency $E_{propeller}$ can be calculated as follows:

$$\eta_{propeller} = \frac{F_T v}{M_{propeller}\,\omega} \qquad \text{Equation [1.6].01}$$

Variable	Description	
$\eta_{propeller}$	Efficiency of the propeller	Symbol [1.6].01
$M_{propeller}$	Moment of Resistance (Moment of Inertia)	Symbol [1.6].02
ω	Angular velocity of propeller	Symbol [1.6].03
F_T	Force of thrust	Symbol [1.6].04
v	Axial velocity of propeller	Symbol [1.6].05

If we consider a stream tube around it, as the mass of air passing through the stream tube must be constant, the increased velocity leads to a contraction of the stream tube passing through the propeller disk, neglecting compressibility.

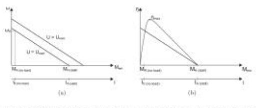


Figure [1.6].2: (a) Angular velocity with respect to torque characteristic. (b) Efficiency with respect to torque. [33] (As taken from source with adjustments for readability)

Designing an efficient propeller is akin to design an efficient wing. First, an optimal aerofoil is established, then a suitable chord and angle of incidence that minimizes the moment of resistance and therefore the coefficient of drag is established. A good propeller designed for a specific aircraft's role (airspeed, altitude, temperature, etc.) should have an efficiency of around 82.5% as given in in figure [1.6].3. [28]

These values are not constant and vary with air speed and rotational speed, or more precisely with the dimensionless propeller advance ratio [28]:

$$J = {}^{v}/_{nd} \qquad \text{Equation [1.6].02}$$

Variable	Description	
J	Dimensionless propeller advance ratio	Symbol [1.6].06
n	Number of blades on propeller	Symbol [1.6].07
d	Diameter of propeller blades	Symbol [1.6].08

During one revolution of the propeller the blades pass through a distance of ${}^{v}/_{n}$, meaning that J is the ratio of this distance and the diameter.

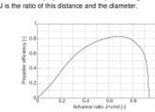


Figure [1.6].3: Propeller efficiency with respect to advance ratio. [28] (Taken form source with adjustments for clarity.)

1.6.4 Variable Pitch Propeller

All these positions assume that the propeller will fly through roughly the same velocity and altitude. If the aircraft is to fly through varying conditions, a variable pitch propeller can be used at the expense of weight and complexity.

This is where the angle of attack or the pitch of the propeller is adjusted as result of changing altitudes and aircraft speeds. It is usually manually changed by a human pilot in manned aircraft, whilst for UAVs most aircraft use fixed propellers. Thus it is by developing an automation model to automatically adjust pitch of the propeller we would be able to achieve greater efficiencies. [29, 31] This, however, should be carefully weighed with the negative of additional weight.

As given in study [31], maximal thrust was increased by 31%, and coefficient of thrust generated (that is, energy efficiency of propeller) increased by 2.6% to 7.5% for various pitch angles. This efficiency increase should be weighed carefully against weight increase of the UAV using mathematical analysis.

1.7 Key Takeaways

After the analysis of factors that can be optimized in the mechanical component of the solar craft, the following can be determined: the main goal optimizing mechanics is to ensure that the minimal amount of energy is required to increase the altitude of the solar craft.

This factor of optimization is chosen as the currency in which the solar craft deals with is altitude or "energy", the greater the altitude the more room the aircraft will have to manoeuvre out of adverse weather and increase the time available it has to charge its batteries before it will need to use them to regain altitude.

To optimize the aircraft mechanically we must consider:

Takeaway Points

Point [1.7].01 Mass of the aircraft.
- a. Through material selection and analysis
- b. Through choice of optimal aerofoil to minimize wing area while still optimal values of Coefficient of Drag and Coefficient of Lift

Point [1.7].02 Drag Coefficient.
- a. Reduction of aerofoil drag through choice of a performant aerofoil shape both at high altitude and at low speeds with a high Oswald efficacy factor
- b. Reduction of parasitic drag through:
  - i. Removal of landing gear or use of aerofoil shape to create a casing around landing gear
  - ii. Choice of performant aerofoil on control surfaces, tail and ailerons
  - iii. Design of payload to be in-line with the fuselage
  - iv. Design of fuselage shape to have a low drag coefficient

Chapter
02

Chapter 2: The Principles of Solar Flight

2.1 Introduction

After the analysis of mechanical components of a conventional aircraft which can be applied to a solar aircraft, the electronic components surrounding solar aircraft must now be analysed.

Only the essential theory required to optimize and deduce whether the proposition of this dissertation is feasible will be analysed.

2.2 The Flow of Energy in a Solar Aircraft

Solar panels are composed of solar cells that are connected together in a given configuration to maximize current, voltage, etc. They usually cover wing, fuselage, and tail surfaces to maximize power output. During the day the solar panels convert light energy into electrical energy. The cumulative energy output during the day depends on the sun's elevation and irradiance in the sky, the angle at which the sun is to the solar panels, and the cloud-cover on a given day. [43]

A converter called the Maximum Power Point Tracker (MPPT) ensures the circuit is running at the maximum power point, thus ensuring that the solar cells and batteries are at the maximum efficiency

The power supplied by the solar panels is used to firstly directly supply energy to propulsion, control, and communication electronics; and second it is used to charge the on-board batteries with any surplus of energy.

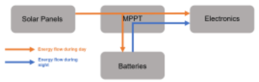


Figure [2.2].1: The energy transfers during night and day of a solar-craft.

During the night, the solar panels do not generate any power and so the batteries are to supply the propulsion, control, and communication electronics until daybreak where a new charge cycle begins. Therein lies the challenge after choosing optimal battery and solar panel technologies, the ratio of solar panels to batteries must be optimized to ensure that the craft is not too heavy nor bulky, but still has enough storage and power production to reach the next charge cycle.

2.3 The Solar Cell

2.3.1 Introduction

The solar cell (also known as a photovoltaic cell) is a device that harnesses solar energy through the photovoltaic effect to generate electricity. Its widespread use in spacecraft applications is due to its ability to provide a non-variable and long-duration source of energy that requires minimal maintenance.

The composition of solar cells typically involves one or more layers of various semiconducting materials. Silicon here is the most commonly utilized material due to its abundance as the second most prevalent element in the Earth's crust [65] thus making it a cost-effective option.

2.3.2 The Working Principles

Figure [2.3].1 shows a simple silicon solar cell consisting of two doped semi-conductor layers of a p-type and a n-type. When sunlight is exposed to the cell, the two layers create charge carriers in the form of electrons and holes. The holes are directed towards the positive or p-layer, while the electrons are directed towards the negative or n-layer. [30]

When a circuit is made using the solar cell, the electrons have to travel through the load (such as a motor) to recombine with the positive holes, this thus results in a current when the cell is exposed to light.

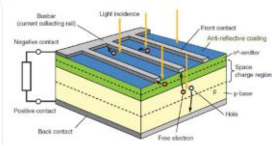


Figure [2.3].1: Working Principle of a solar cell. [30] (as taken from source with adjustments for clarity)

2.3.3 Solar Irradiance

Solar irradiance is the energy output per unit of time by the sun per unit of area, in other words, it is the power output of the sun per unit of area. Different wavelengths of light have a different spectral irradiance (meaning the power output of the sun per unit area per unit of wavelength). Standing under the sun we feel 100% of the total spectral irradiance on our skin (the total area under the line given in the figure [2.3].2 thereby the solar irradiance of the sun), solar cells do not work the same. Based on their band gap (which is based on the type of semiconductor used) these cells can only "feel" or harvest energy from a given section of the entire electromagnetic radiation emitted by the sun.

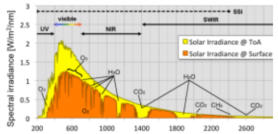


Figure [2.3].1: Working Principle of a solar cell. [72] (as taken from source with adjustment to y-axis to read spectral solar irradiance)

2.3.4 The Types of Solar Cells

It should be first noted that the vast majority of solar cells are composed of elements for groups III, IV, and V. The main reasons for this are as follows, it is important to note these features as it allows us to choose relevant materials that may have surround literature on them.

(1) Optimal Band Gap: The band gap of these elements is ideal for solar energy conversion. This property is crucial for absorbing sunlight and converting it into electricity. Silicon (Group IV element) has a band gap that efficiently absorbs a wide range of the solar spectrum. Additionally, compounds formed from Group III and V elements can have tuneable band gaps allowing them to be optimized for the most energy dense wavelength of light as given in figure [2.3].2 [40, 41]
(2) Controllable Electrical Conductivity: These elements can be easily doped to alter their electrical conductivity thereby making it easy to create p-type and n-type semiconductors thus creating highly stable cells and highly tuned to be efficient solar cells. [40]
(3) Desirable Chemical and Physical Properties: Elements from these groups have chemical and physical properties that are favourable for solar cell fabrication, namely, stability under operating conditions and abundance in nature (such as silicon [65]). [40, 41]

There are vast range of types of solar cells in existence which can be categorized based on the type of material, fabrication process, substrate used, etc.

We can first split solar cells into the main material used in the creation of the cells:

(1) Silicon, silicon-based solar cells are used due to their relatively high efficiency, high silicon abundance, low cost.
Silicon solar cells can be split into three main categories based on the type of crystal used:
    a. Monocrystalline: this is where one singular pure and large silicon crystal is used to create the cell, this thus results in a high efficiency at the expense of a high cost. [47]
    b. Polycrystalline: this is where the structure of the cell is composes of crystals of varying size and orientation, as result the cost of solar cells are cheaper as the most pure silicon need not be used and the manufacturing process is simplified, this is at the expense of a lower efficiency. [47, 49]
    c. Amorphous: this is where a silicon is deposited on substrate material (usually glass, but it can be a large range of materials including flexible materials) resulting in a 1 µm film, this results in a very low efficiency. The production cost of this type of panel is very low. [47, 49]
(2) Compound Solar Cells, based on compounds such as gallium arsenide, cadmium telluride, copper indium dieselenide, etc. Although these cells are more expensive, they are more efficient due a tuneable band gap, superior physical and chemical properties, and higher carrier mobility. [49]
(3) Other types not suitable for study due to low stability [66] and low efficiency [42]
    a. Polymer Solar cells
    b. Dye Sensitized Solar Cells
    c. Organic Cells

Based on the above analysis we are able to narrow down the interactive graph surrounding the data of the best research-cell efficiencies [42] to solar cells that are practicably viable for solar aircraft based on their:

(1) Efficiency, it must be relatively high as the solar craft would be massive, perhaps exceeding the size of the observable universe if the mathematical model is allowed to iterate till infinity
(2) Manufacturing Process and thereby cost, the manufacturing process must be relatively feasible to allow for stable solar cells that have stable efficiencies to ensure that the model given here is indeed as close to the real world as possible.

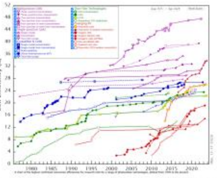


Figure [2.3].3: Interactive graph before narrowing down viable cells based on aforementioned criteria. [42]

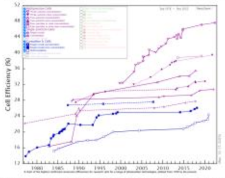


Figure [2.3].4: Interactive graph after narrowing down viable cells based on aforementioned criteria. [42]

2.3.5 Balancing the Current and Voltage of Solar Cell

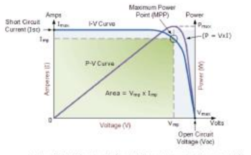


Figure [2.3].5: IV Characteristic Curve of a Solar cell at a constant temperature. [48]

As given in figure [2.3].5, when the terminals of the solar cell are not connected, $i = 0$ and $V = V_{max}$ which is also called the open circuit voltage, V_{OC}. The power that the cell provides is zero here as:

$$\begin{aligned} & P = iV \\ \Rightarrow\ & P_{sc} = iV_{max} \qquad \Leftrightarrow\ P_{sc} = iV_{OC} \\ \Rightarrow\ & P_{sc} = (0)V_{max} \\ \Rightarrow\ & P_{sc} = 0 \end{aligned}$$

When the solar cell is short circuited by connecting a short near-zero piece of wire, the $V = 0$ and $i = i_{max}$ which is also called open circuit current, i_{sc}. The power that the cell provides is zero here as:

$$\begin{aligned} & P = iV \\ \Rightarrow\ & P_{sc} = iV \qquad \Leftrightarrow\ P_{sc} = i_{SC}V \\ \Rightarrow\ & P_{sc} = i_{max}(0) \\ \Rightarrow\ & P_{sc} = 0 \end{aligned}$$

This therefore means that to obtain the maximum power output of the solar cell both i and V must be maximized as:

$$P_{sc} \propto i \qquad P_{sc} \propto V$$

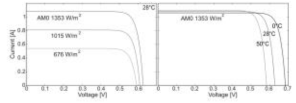


Figure [2.3].6: IV Characteristic curve of a solar cell with regard to ambient temperature around solar cell. [48]

Efficiency of the solar cell is directly proportional to the power output of the cell, this means to maximize the power output of the cell would also be to maximize the efficiency of the solar cell, this reasoning can be attributed to:

$$\begin{aligned} & \eta_{sc} = \frac{P_{useful\ output}}{P_{input}} \qquad & P_{sc} = iV \\ \Rightarrow\ & \eta_{sc} = \frac{i_{MPP}V_{MPP}}{P_{input}} \qquad & \Leftrightarrow\ P_{sc} = i_{MPP}V_{MPP} \\ \Rightarrow\ & \eta_{sc} = \frac{i_{MPP}V_{MPP}}{I_{max}A_{sc}} \qquad & \Leftrightarrow\ I_{max} = {}^{P_{sun}}/_{A_{sc}} \\ \Rightarrow\ & \eta_{sc} = \frac{i_{MPP}V_{MPP}}{I_{max}A_{sc}} \qquad & \text{Equation [2.3].01} \\ \Rightarrow\ & \eta_{sc} \propto P_{sc} \qquad & \text{Equation [2.3].02} \end{aligned}$$

As given in figure [2.3].6, solar cells are most performant at lower temperatures as solar cells are able to output a current at higher voltages thus withstanding higher voltages, this therefore results in a large area under the graph due to $P_{sc} = iV$. The efficiency of the solar cell is higher at lower temperatures as there is a greater energy output per unit of time (power) due to $\eta_{sc} \propto P_{sc}$.

Takeaway Points	
Point [2.3].01	The mathematical model to be created must consider the average temperature of the Earth or the location where solar irradiance data is taken to ensure the conclusivity of study on the feasibility of continuous solar flight.

2.4 Energy Storage Systems

2.4.1 Introduction

Whilst literature surrounding energy storage on solar aircraft is sparse and therefore poses challenges when determining feasible technologies to input as parameters in the mathematical models in chapter 3 and chapter 4. A solution to this problem can be found in using the parallels found in solutions to similar problems in storing energy on manned and unmanned spacecraft to determine feasible methods of energy storage for solar aircraft. This can be attributed to the following reasons:

(1) Energy systems designed for outer-space are hardened against extreme temperature shifts. [44] Energy storage devices need to be able to withstand constant temperature shifts based on the day-night cycle on Earth, this is especially the case at higher altitudes where there are no large bodies like oceans, seas, lakes, or land to act as "heat batteries". Without considering this factor in choosing the optimum battery storage device for a solar craft it could result in premature failure which would be far from "continuous", for this reason this must be taken into consideration.
(2) Spacecraft components, including energy storage systems, are designed to be radiation-hardened to survive in the harsh space environment. [44] Cosmic radiation also increases at higher altitudes on Earth [45], if cosmic radiation is not taken into account when choosing energy storage systems it could result in battery capacity degradation over large periods of time as solar aircraft may fly at high altitudes. Adapting these radiation-hardened technologies can increase the durability and reliability of solar aircraft systems. Without considering this factor in choosing the optimum battery storage device for a solar craft it could result in premature failure which would be far from "continuous", for this reason this must be taken into consideration.
(3) Space missions sometimes lack constant energy sources for vast periods of their journey, just as solar aircraft lack solar energy due to the day-night cycle. The solutions the spaceflight industry has developed can be applied to solar aircraft almost directly due to the similar environment both craft face.
(4) Launching space craft is costly [46], this therefore means that solar aircraft are highly optimized to be weight efficient, as minimizing weight reduces launch costs and thereby allows for more craft to be launched in a given budget. This focus on lightweight yet efficient energy storage systems can be directly applicable to solar aircraft, where weight is a critical factor for flight duration and efficiency.

As a result, based on a recent NASA analysis into energy storage technologies for spacecraft [43], the following energy storage methods are available:

Type of energy storage device	Examples
Chemical	Hydrogen, biofuels
Electrochemical	Chemical batteries, fuel cells, solid state batteries, flow batteries
Electrical	Capacitors, supercapacitors, superconducting magnetic energy storage
Mechanical	Compressed air, flywheels

Table [2.4].1: Outline of viable energy storage medium based on spacecraft design.

Based on the following criteria, we are able to determine the most practical and feasible method of energy storage to inform the mathematical model in the following chapters.

(1) Relatively high gravimetric energy density
(2) Stability, must be able to last for longer periods of time as the battery would cycle charge daily
(3) Availability, must be mainstream to aid data gathering and therefore allow for a more accurate mathematical model to be drawn up

It can be determined that electrochemical storage of energy is the most suitable method of storing energy for continuous solar flight based on the following analysis:

(1) Lithium ion batteries have the highest gravimetric energy density of all mainstream (non-research) level batteries. [53] See figure [3.4].3.
(2) Lithium ion batteries last for a relatively long set of charge cycles whilst still being high available and very energy dense. [56, 57]
(3) Lithium ion batteries commercial demand is sharply on the rise due to the increase in demand of electric vehicles, this therefore means data surrounding lithium ion batteries is constantly up-to-date and vast. [55]

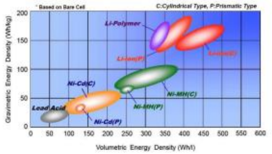


Figure [2.4].1: Gravimetric energy density of various mainstream electrochemical batteries. [53] (taken from NASA)

Takeaway Points	
Point [2.4].01	The energy storage system to be chosen for determining parameters in the mathematical model should be electrochemical batteries, specifically of the lithium-ion or lithium-ion-polymer type.

2.4.2 Electrochemical Battery Working Principles

Electrochemical batteries convert energy from a chemically stored medium into electrical energy when discharged. As given in figure [2.4].2, the basic composition of a battery is two conducting plates called the anode and cathode which are immersed in a solution called an electrolyte, once all the reactants are connected in a complete circuit electrons and ions are able to flow thus producing a potential difference and thereby discharging the battery. [58, 59]

Batteries are rechargeable if the reaction is reversible, if the battery is rechargeable it is referred to as a secondary battery [58], else it is a primary battery if it non-rechargeable. For the given use-case of a solar aircraft secondary batteries will be used so that they can be recharged during the day and discharged at night.

In the case of lithium ion batteries, the name refers to lithium as an element in a larger compound used as the cathode and the anode as graphite [60] (allotrope of carbon [61]), some compounds include Lithium Manganese Oxide, Lithium Nickel Manganese Cobalt Oxide, etc. [60]

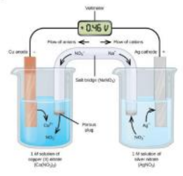


Figure [2.4].2: Electrochemical battery basic architecture. [59]

2.4.3 Electrochemical Battery Charge and Discharge Process

First, charging and discharging must be carefully managed to ensure that energy is not wasted (this ensuring maximal efficiency of charge and discharged day/night cycle) [62], and to also ensure that the battery does not overheat and perhaps catch on fire. For charging there is a two phase process that is managed by a MPPT, see figure [2.4].3.

Second, batteries of a high energy density are usually only able to provide low currents as given in chapter 4 and in figure [2.4].4, this means that electrical systems must be designed with low voltages in mind otherwise efficiency of the battery is reduced under high loads, or buffer batteries or step-up transformers must be utilized. [62] This also means that an MPPT must be utilized for discharging process too to ensure that a battery is not discharged too quickly ensuring maximum efficiency at all times.

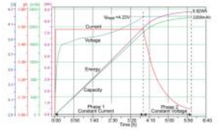


Figure [2.4].3: Typical lithium ion battery charge cycle. [62]

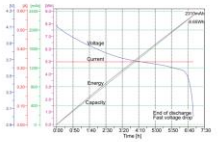


Figure [2.4].4: Typical lithium ion battery discharge cycle. [62]

Takeaway Points	
Point [2.4].02	Charing and discharging batteries should be managed by MPPT controller and therefore we must account for the non-100% efficiency of charging and discharging both from the hardware and software side of the MPPT.
Point [2.4].03	Electrical systems must be designed with low voltages in mind otherwise efficiency of the battery is reduced under high loads, or buffer batteries or step-up transformers must be utilized. This may need to be considered in the mathematical model.

2.5 The Maximum Power Point Tracker (MPPT)

2.5.1 Introduction

MPPT (Maximum Power Point Tracker) charge controllers consist of two parts:

(1) Hardware to control voltage and current across the solar cell and lithium ion battery through the use of a circuit similar to a DC-DC converter for stepping up and down voltages. [63]
(2) Software algorithms to determine the exact voltage and current of the maximum power point [63] and to predict it's variation in sufficiently advanced algorithms. [64]

2.5.2 MPPT Working Principles

As given in figure [2.3].5, the use of a MPPT charge controller also ensures that $i_{MPP}V_{MPP}$ are maintained thereby ensuring high solar cell efficiency as given by $P_{sc} = iV$ and $\eta_{sc} \propto P_{sc}$.

Takeaway Points	
Point [3.5].01	A MPPT controller should be used to ensure that the $i_{MPP}V_{MPP}$ is achieved at all times and thereby ensure the maximum efficiency of the solar cell (and battery) ensuring that infinite solar flight has the best chance of being feasible. The mass of such a system must be factored into the model.

2.5.3 MPPT Algorithms

There are multiple algorithms that are able to find and maintain the maximum power point such as perturb & observe (hill climbing), incremental conductance, machine learning based algorithms [34], etc. [64].

Takeaway Points	
Point [3.5].02	Depending the variability of the environment the solar aircraft could be deployed in (due to variable mission criteria), more advanced algorithms that employ machine learning may be beneficial to increase efficiency of the solar aircraft, it should be noted that the aircraft would need to be connected to a high speed communication network to transfer commands from a power computer machine running the machine learning algorithm as the solar aircraft does not have the energy nor mass to spare to run such a resource costly algorithm.
Point [3.5].03	Algorithmic efficiency must be factored into the mathematical model to ensure conclusivity of the model.

2.6 The Electric Motor

There are two types of categories for motors:

(1) Direct Current (DC) motors
(2) Alternating Current (AC) motors

For the present case of solar-powered flight DC motors will be used as the lithium ion batteries output DC current and converting to AC would add extra mass that would bring no benefit.

For similar reasons explained in chapter 3.4.1, determining a suitable motor for solar aircraft can be found using the parallels found in manned and unmanned spaceflight.

As given in a series of publications called lessons learned at NASA [64], brushless DC motors are the most suitable candidates for solar flight as:

(1) Suitable for high RPM (rotations per minute) applications such as rotation of a propeller
(2) Lightweight applications such as here in a solar aircraft due to their high power output to mass ratio
(3) Low thermal emission application, thus meaning that energy loss through non-useful work is minimized thus meaning that efficiency is maximized. This can be attributed to no brushes used to connect the coils to a commutator as the coils are fixed in a BLDC motor, this therefore means there is less friction
(4) Long-range applications as these motors can last for very long periods of time due to no wear-down of carbon brushes as there are no brushed present.

Takeaway Points	
Point [2.6].01	BLDC motors are the most efficient with the highest power output to mass ratio thus meaning that mass is conserved on the solar aircraft. BLDC motors are therefore the most suitable type for our mathematical model.
Point [2.6].02	DC motors are to be used in the solar aircraft, this therefore means DC current motor dynamics are to be applied to the mathematical model.

Section.5 Appendices

5.A List of Symbols

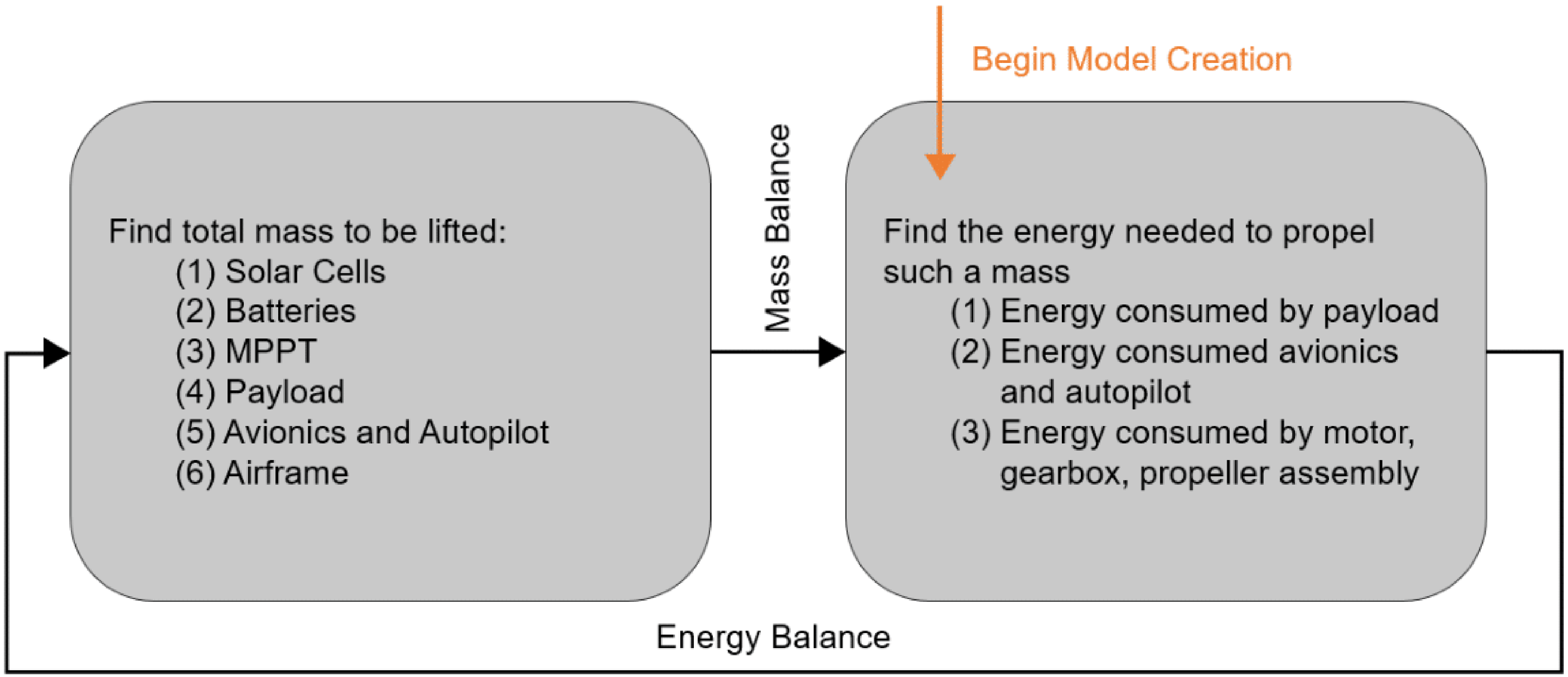
Variable	Description	Unit	
F_x	Forces in the x axis	[N]	Symbol [1.2].01
F_y	Forces in the y axis	[N]	Symbol [1.2].02
F_D	Force due to drag, previously F_{Drag}, henceforth F_D.	[N]	Symbol [1.4].01
C_D	Coefficient of Drag		Symbol [1.4].02
F_L	Force due to lift, previously F_{Lift}, henceforth F_L.	[N]	Symbol [1.4].03
C_L	Coefficient of Lift		Symbol [1.4].04
ρ	Density of air	[kg m^{-3}]	Symbol [1.4].05
A_W	Area of the wing	[m^2]	Symbol [1.4].06
v	Speed of aerofoil relative to the air (Relative airspeed)	[m s^{-1}]	Symbol [1.4].07
c	Wing chord		Symbol [1.4].08
μ	Bulk viscosity or Dynamic viscosity		Symbol [1.4].09
ψ	Kinematic Viscosity		Symbol [1.4].10
S	Wing span	[m]	Symbol [1.4].11
A_r	Aspect ratio		Symbol [1.4].12
$C_{D\ Induced}$	Induced Drag Coefficient		Symbol [1.4].13
e_o	Oswald Efficiency Factor		Symbol [1.4].14
U	Terminal voltage from supply to motor	[V]	Symbol [1.5].01
r_a	Terminal resistance	[Ω]	Symbol [1.5].02
i	Current	[A]	Symbol [1.5].03
k_u	Voltage constant	[V s rad^{-1}]	Symbol [1.5].04
k_m	Velocity constant	[rad V^{-1} s^{-1}]	Symbol [1.5].05
M_{em}	Electromagnetic moment		Symbol [1.5].06
ω_{mot}	Angular speed of motor shaft	[rad s^{-1}]	Symbol [1.5].07
i	Current final	[A]	Symbol [1.5].08
i_0	Current initial	[A]	Symbol [1.5].09
M_{mot}	Moment (Torque) due to motor turn force	[N m]	Symbol [1.5].10
M_{fs}	Moment (Torque) due to internal mechanical friction	[N m]	Symbol [1.5].11
$\eta_{propeller}$	Efficiency of the propeller		Symbol [1.6].01
$M_{propellor}$	Moment of Resistance (Moment of Inertia)		Symbol [1.6].02
ω	Angular velocity of propeller	[rad s^{-1}]	Symbol [1.6].03
F_T	Force of thrust	[N]	Symbol [1.6].04
v	Axial velocity of propeller	[m s^{-1}]	Symbol [1.6].05
J	Dimensionless propeller advance ratio		Symbol [1.6].06
n	Number of blades on propeller		Symbol [1.6].07
d	Diameter of propeller blades	[m]	Symbol [1.6].08
F_T	Force due to thrust, previously F_{Lift}	[N]	Symbol [3.X].01
F_W	Force due to weight, previously F_{Weight}	[N]	Symbol [3.X].02
P_{lvl}	Power consumed during level flight	[W]	Symbol [3.X].03
P_{usfl}	Power spent to create useful work	[W]	Symbol [3.X].04
P_{av}	Power consumed by avionics and autopilot	[W]	Symbol [3.X].05
P_{pld}	Power consumed by payload	[W]	Symbol [3.X].06
P_{tot}	Total power consumed	[W]	Symbol [3.X].07
P_{max}	Maximum Power Output	[W]	Symbol [3.X].08
η_{tot}	Total Efficiency		Symbol [3.X].09
η_{ctrl}	Efficiency of motor controller		Symbol [3.X].10
η_{mot}	Efficiency of motor		Symbol [3.X].11
η_{grb}	Efficiency of gearbox		Symbol [3.X].12
η_{plr}	Efficiency of propeller		Symbol [3.X].13
η_{BEC}	Efficiency of step-down converter		Symbol [3.X].14
η_{chrg}	Efficiency of battery charge		Symbol [3.X].15
η_{dchrg}	Efficiency of battery discharge		Symbol [3.X].16
η	Efficiency		Symbol [3.X].17
η_{sc}	Efficiency of solar cells		Symbol [3.X].18
η_{cbr}	Efficiency of curved solar panels		Symbol [3.X].19
η_{mppt}	Efficiency of MPPT Charge Controller		Symbol [3.X].20
$\eta_{mppt\ conv}$	Efficiency of DC to DC converter of MPPT		Symbol [3.X].21
$\eta_{mppt\ algor}$	Efficiency of tracking algorithm of MPPT		Symbol [3.X].22
k_{wthr}	Arbitrary weather constant		Symbol [3.X].23
k_{mppt}	Mass to power ratio of MPPT	[kg W^{-1}]	Symbol [3.X].24
E_{tot}	Total energy consumed	[J]	Symbol [3.X].25
T_{tot}	Total time elapsed, cumulative time period	[s]	Symbol [3.X].26
T_{day}	Time period of day, time from sunrise to sunset	[s]	Symbol [3.X].27
T_{night}	Time period of night, time from sunset to sunrise	[s]	Symbol [3.X].28
φ	Sunlight Day density		Symbol [3.X].29
I_{max}	Maximum sun irradiance	[W m^{-2}]	Symbol [3.X].30
A_{sc}	Area of solar panels	[m^2]	Symbol [3.X].31
κ	2D Density	[kg m^{-2}]	Symbol [3.X].32
κ_{sc}	Mass density of solar cells	[kg m^{-2}]	Symbol [3.X].33
κ_{add}	Mass density of additional mass around solar panels	[kg m^{-2}]	Symbol [3.X].34
ρ	3D Density	[kg m^{-3}]	Symbol [3.X].35
V	Volume	[m^3]	Symbol [3.X].36
A	Area	[m^2]	Symbol [3.X].37
m	Mass	[kg]	Symbol [3.X].38
m_{sc}	Mass of solar cells	[kg]	Symbol [3.X].39
m_{mppt}	Mass of MPPT Charge controller	[kg]	Symbol [3.X].40
$m_{bat\ max}$	Mass of battery if the battery was maximally efficient or 100% efficient	[kg]	Symbol [3.X].41
Ψ	Gravimetric Energy Density	[J kg^{-1}]	Symbol [3.X].42
Ψ_{bat}	Gravimetric Energy Density of Battery	[J kg^{-1}]	Symbol [3.X].43

The Sustained Focus

01	Contents
02	Title Analysis
03	The Why behind this EPQ
04	The Methodology to Answer the Question Posed by this EPQ
05	Schools of Focus
06	Are the Schools of Focus Connected?
07	The Solar-powered Focus
08	The Sustained Focus
09	Forming the Model
10	The Autonomous Focus
11	Conclusions
12	So why aren’t we seeing this right now?
13	Project Management
14	Motivations
15	Looking Back
16	Looking Ahead

Discrete and Iterative Approach

Continuous and Analytical Approach


Begin Model Creation
Find total mass to be lifted:
(1) Solar Cells
(2) Batteries
(3) MPPT
(4) Payload
(5) Avionics and Autopilot
(6) Airframe
Mass Balance
Find the energy needed to propel such a mass
(1) Energy consumed by payload
(2) Energy consumed avionics and autopilot
(3) Energy consumed by motor, gearbox, propeller assembly
Energy Balance

Chapter 03

Chapter 3: The Optimization of the Mechanical and Electrical Design

3.1 Introduction

3.1.1 Overview

It should first be noted to simplify this chapter the descriptions and units of various symbols used in models in this chapter can be found in Section.5 Appendices → 5.A through to 5.D.

This chapter provides the complete method to optimizing the characteristic mentioned previously in the review of literature and theory.

The aim of our study is to determine the feasibility of solar-powered flight that can be sustained allowing an aircraft to remain in the air for a theoretically infinite period of time.

To reduce the complexity of the following mathematics, the aircraft is taken to be flying in level flight. While complexity and detail has been reduced, the overall outcome of the study should remain unaffected, this is because the aircraft must be able to develop power whilst in level flight during that day to charge its batteries rather than having to rely on thermal updrafts in air or careful altitude planning.

Techniques to further supplement an already efficient aircraft such as rising thermals, machine learning MPPT, better wing structure, etc. are discussed in chapter 5.3.

3.1.2 Methodology

As given in chapter 1 and 2, we need to optimize the following two balances:

(1) Balance the weight of the force of the mass of the aircraft as a whole
(2) Balance the energy constraints of the aircraft by ensuring that energy collected during the day exceed energy expended and that batteries store enough energy to withstand a night without power generation.

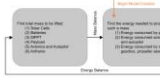


Figure [3.1].1: Graphically represented balances

5.B List of Formulae

Equation	Number
$\Sigma F_x = ma$	Equation [1.2].01
$F_{Thrust} - F_{Drag} = ma$	Equation [1.2].02
$\Sigma F_y = ma$	Equation [1.2].03
$F_{Lift} - F_{Weight} = ma$	Equation [1.2].04
$F_D = C_D \frac{\rho}{2} A_W v^2$	Equation [1.4].01
$F_D = C_D \frac{\rho}{2} A_W v^2$	Equation [1.4].01
$R_e = \frac{vc}{\psi}$	Equation [1.4].04
$\frac{1}{\psi} = \frac{\rho}{\mu}$	Equation [1.4].05
$A_r = \frac{S^2}{A_w}$	Equation [1.4].06
$C_{D\ Induced} = \frac{C_L^2}{\pi e_o A_r}$	Equation [1.4].07
$C_{D\ Overall} = C_{D\ Induced} + C_{D\ Parasite} + C_{D\ Aerofoil}$	Equation [1.4].08
$\begin{cases} U = r_a i + k_u \omega_{mot} \\ M_{em} = k_m i \end{cases}$	Equation [1.5].01
$\omega_{mot} = \frac{U - r_a i}{k_u}$	Equation [1.5].02
$M_{mot} = M_{em} - M_{f_s}$	Equation [1.5].03
$M_{mot} = k_m (i - i_0)$	Equation [1.5].04
$U = r_a \left(\frac{M_{mot}}{k_m} + i_0\right) + k_u \omega_{mot}$	Equation [1.5].05
$M_{mot} = \frac{k_m^2}{r_a} \omega_{mot} + k_m \left(\frac{U}{r_a} - i_0\right)$	Equation [1.5].06
$\omega_{mot} = -\frac{r_a}{k_m^2} M_{mot} + \left(\frac{U - r_a i_0}{k_m}\right)$	Equation [1.5].07
$\eta_{propeller} = \frac{F_T v}{M_{propellor} \omega}$	Equation [1.6].01
$J = {}^{v}/_{nd}$	Equation [1.6].02
$\eta_{sc} = \frac{i_{MPP} V_{MPP}}{I_{max} A_{sc}}$	Equation [2.3].01
$\eta_{sc} \propto P_{sc}$	Equation [2.3].02
$F_T = C_D \frac{\rho}{2} A_W v^2$	Equation [3.3].01
$C_L \frac{\rho}{2} A_W v^2 = mg$	Equation [3.3].02
$v = \sqrt{\frac{2mg}{C_L \rho A_W}}$	Equation [3.3].03
$P_{level} = F_T v \cos(\theta_{Fv})$	Equation [3.3].04
$P_{level} = \frac{C_D}{C_L^{3/2}} \sqrt{\frac{2(mg)^3}{A_W \rho}}$	Equation [3.3].05
$P_{lvl} = \left(\frac{C_D}{C_L^{3/2}} \sqrt{\frac{2 A_r g^3}{\rho}}\right) \left(\frac{m^{3/2}}{S}\right)$	Equation [3.3].06
$P_{tot} = \frac{1}{\eta_{ctrl} \eta_{mot} \eta_{grb} \eta_{plr}} (P_{lvl}) + \frac{1}{\eta_{BEC}} (P_{av} + P_{pld})$	Equation [3.3].07
$E_{tot} = P_{tot} \left(T_{day} + \frac{T_{night}}{\eta_{chrg} \eta_{dchrg}}\right)$	Equation [3.3].08
$T_{night} + T_{day} = 24$	Equation [3.3].09
$\varphi = \frac{I_{max} T_{day}}{\pi/2} k_{wthr}$	Equation [3.4].01
$E_{tot} = \left(\frac{I_{max} T_{day}}{\pi/2} k_{wthr}\right) A_{sc}$	Equation [3.4].02
$E_{tot} = \left(\frac{I_{max} T_{day}}{\pi/2} k_{wthr}\right) A_{sc} (\eta_{sc} \eta_{cbr} \eta_{mppt})$	Equation [3.4].03
$m = m_{fixed} + m_{af} + m_{sc} + m_{mppt} + m_{bat} + m_{prop}$	Equation [3.5].01
$m_{fixed} = m_{av} + m_{pld}$	Equation [3.5].02
$W_{af} = 8.764 (nSA_w^3)^{0.463}$	Equation [3.5].03
$W_{af} = 8.764 n^{0.463} s^{0.788} A_r^{0.467}$	Equation [3.5].04
$m_{af} = \frac{8.764 n^{0.463} s^{0.788} A_r^{0.467}}{g}$	Equation [3.5].05
$m_{af} = \frac{15.19 s^{0.656} A_r^{0.467}}{g}$	Equation [3.5].06
$A_{sc} = P_{tot} \left(1 + \frac{T_{night}}{T_{day}} \frac{1}{\eta_{chrg} \eta_{dchrg}}\right) \left(\frac{\pi}{2 \eta_{sc} \eta_{cbr} \eta_{mppt} k_{wthr} I_{max}}\right)$	Equation [3.5].07
$m_{sc} = (\kappa_{sc} + \kappa_{add}) A_{sc}$	Equation [3.5].08
$m_{mppt} = k_{mppt} P_{max}$	Equation [3.5].09
$\eta_{mppt} = \eta_{mppt\ conv} \eta_{mppt\ algor}$	Equation [3.5].10
$P_{max} = 2 \eta_{sc} \eta_{cbr} \eta_{mppt\ conv} \eta_{mppt\ algor} I_{max} A_{sc}$	Equation [3.5].11
$m_{mppt} = k_{mppt} 2 \eta_{sc} \eta_{cbr} \eta_{mppt\ conv} \eta_{mppt\ algor} I_{max} A_{sc}$	Equation [3.5].12
$\eta = 95.06\% \approx 95\%$	Equation [3.5].13
$m_{bat} = \frac{T_{night} P_{tot}}{\eta_{dchrg} \Psi_{bat}}$	Equation [3.5].14
$k_{prop} = k_{mot} k_{grbx} k_{grb} k_{plr}$	Equation [3.5].01
$m_{prop} = k_{mot} k_{grb} k_{ctrl} k_{plr} P_{lvl}$	Equation [3.5].02
$m = 33.3032 + (0.8327) A_{sc} + (0.5072) P_{tot} + (0.0007602) P_{lvl}$	Equation [4.3].01
$P_{lvl} = (0.107296) m^{3/2}$	Equation [4.3].02
$P_{tot} = (1.5020)(P_{lvl}) + 140$	Equation [4.3].03
$A_{sc} = P_{tot} (0.01659975)$	Equation [4.3].04

Forming the Model

01 Contents

02 Title Analysis
03 The Why behind this EPQ

04 The Methodology to Answer the Question Posed by this EPQ
05 Schools of Focus
06 Are the Schools of Focus Connected?

07 The Solar-powered Focus
08 The Sustained Focus
09 Forming the Model
10 The Autonomous Focus

11 Conclusions
12 So why aren’t we seeing this right now?

13 Project Management
14 Motivations

15 Looking Back
16 Looking Ahead

$$A_{sc} = P_{tot}\left(1+\frac{T_{night}}{T_{day}}\frac{1}{\eta_{chrg}\eta_{dchrg}}\right)\left(\frac{\pi}{2\eta_{sc}\eta_{cbr}\eta_{mppt}k_{wthr}}\right)$$

$$P_{lvl} = \left(\frac{C_D}{C_L^{3/2}}\sqrt{\frac{2A_r g^3}{\rho}}\right)\left(\frac{m^{3/2}}{S}\right)$$

$$P_{tot} = \frac{1}{\eta_{ctrl}\eta_{mot}\eta_{grb}\eta_{plr}}(P_{lvl}) + \frac{1}{\eta_{BEC}}(P_{av}+P_{pld})$$

$$m_{fixed} = m_{av} + m_{pld}$$

$$m_{sc} = (\kappa_{sc}+\kappa_{add})A_{sc}$$

$$m_{bat} = \frac{T_{night}}{\eta_{dchrg}\kappa_{bat}}P_{tot}$$

$$m = m_{fixed} + m_{af} + m_{sc} + m_{mppt} + m_{bat} + m_{prop}$$

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$$m_{bat} = \frac{T_{night}}{\eta_{dchrg}\kappa_{bat}}P_{tot}$$

$$A_{sc} = P_{tot}\left(1+\frac{T_{night}}{T_{day}}\frac{1}{\eta_{chrg}\eta_{dchrg}}\right)\left(\frac{\pi}{2\eta_{sc}\eta_{cbr}\eta_{mppt}k_{wthr}I_{max}}\right)$$

$$\Longrightarrow\ m = k_{mppt}2\eta_{sc}\eta_{cbr}\eta_{mppt\ conv}\eta_{mppt\ algor}I_{max}A_{sc}$$

$$m = m_{fixed} + m_{af} + m_{sc} + m_{mppt} + m_{bat} + m_{prop}$$

$$P_{lvl} = \left(\frac{C_D}{C_L^{3/2}}\sqrt{\frac{2A_r g^3}{\rho}}\right)\left(\frac{m^{3/2}}{S}\right)$$

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$$m_{bat} = \frac{T_{night}}{\eta_{dchrg}\kappa_{bat}}P_{tot}$$

$$m_{mppt} = k_{mppt}2\eta_{sc}\eta_{cbr}\eta_{mppt\ conv}\eta_{mppt\ algor}I_{max}A_{sc}$$

$$m_{sc} = (\kappa_{sc}+\kappa_{add})A_{sc}$$

$$A_{sc} = P_{tot}\left(1+\frac{T_{night}}{T_{day}}\frac{1}{\eta_{chrg}\eta_{dchrg}}\right)\left(\frac{\pi}{2\eta_{sc}\eta_{cbr}\eta_{mppt}k_{wthr}I_{max}}\right)$$

$$m = m_{fixed} + m_{af} + m_{sc} + m_{mppt} + m_{bat} + m_{prop}$$

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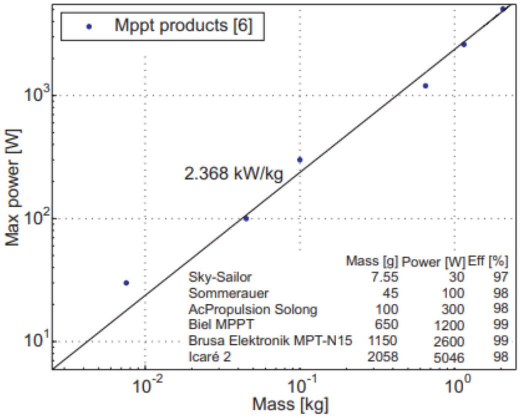
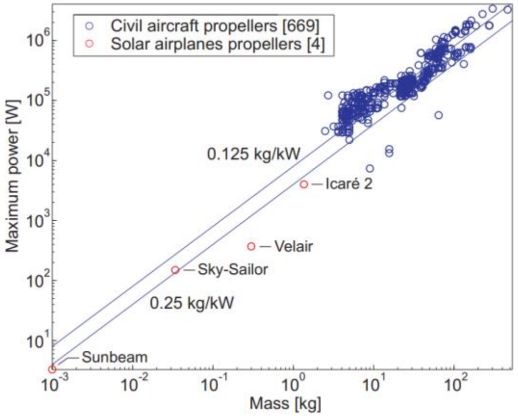
$$m_{bat} = \frac{T_{night}}{\eta_{dchrg}\kappa_{bat}}P_{tot}$$

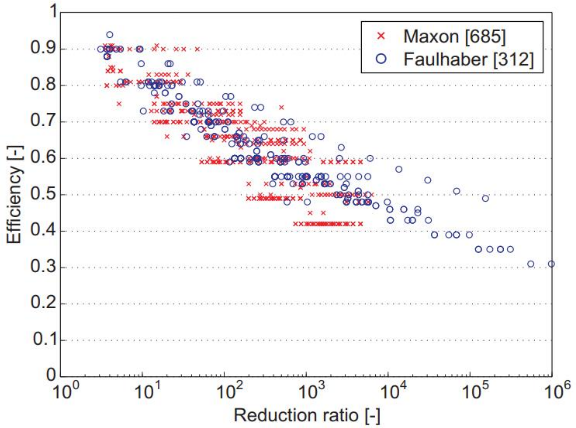
$$m_{mppt} = k_{mppt}2\eta_{sc}\eta_{cbr}\eta_{mppt\ conv}\eta_{mppt\ algor}I_{max}A_{sc}$$

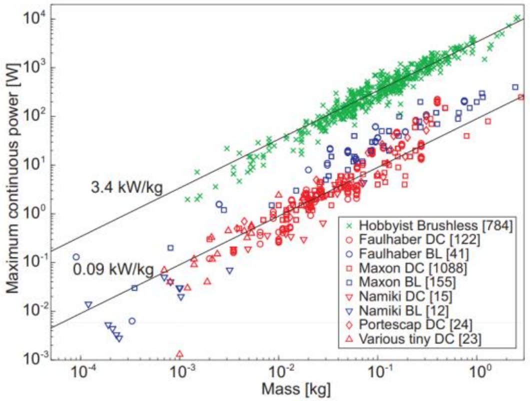
$$m_{sc} = (\kappa_{sc}+\kappa_{add})A_{sc}$$

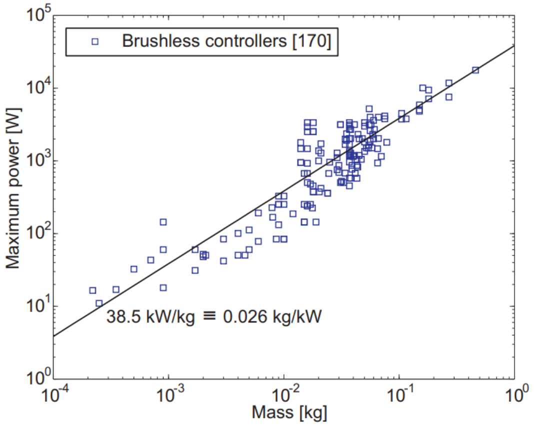
$$A_{sc} = P_{tot}\left(1+\frac{T_{night}}{T_{day}}\frac{1}{\eta_{chrg}\eta_{dchrg}}\right)\left(\frac{\pi}{2\eta_{sc}\eta_{cbr}\eta_{mppt}k_{wthr}I_{max}}\right)$$

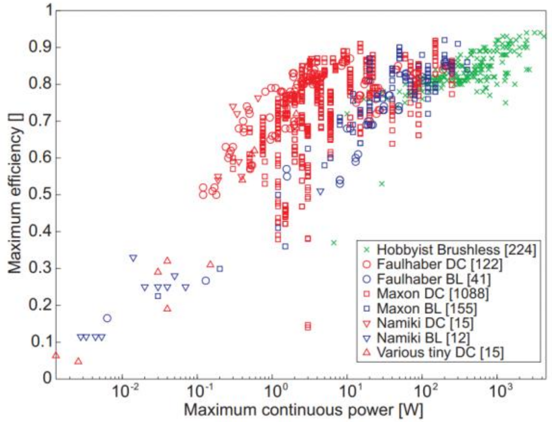

Mppt products [6]
2.368 kW/kg
Max power [W]
Mass [kg]
Mass [g] Power [W] Eff [%]
Sky-Sailor 7.55 30 97
Sommerauer 45 100 98
AcPropulsion Solong 100 300 98
Biel MPPT 650 1200 99
Brusa Elektronik MPT-N15 1150 2600 99
Icaré 2 2058 5046 98

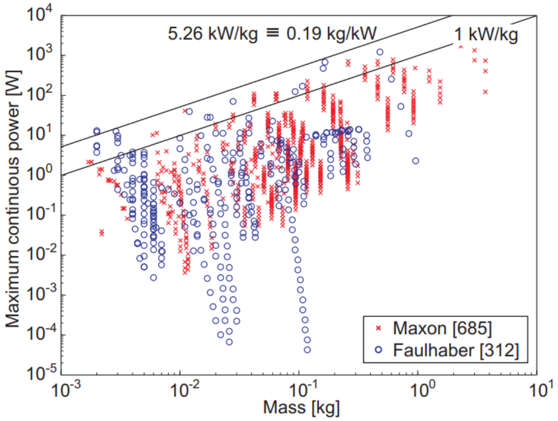

Civil aircraft propellers [669]
Solar airplanes propellers [4]
0.125 kg/kW
0.25 kg/kW
Icaré 2
Velair
Sky-Sailor
Sunbeam
Maximum power [W]
Mass [kg]


Maxon [685]
Faulhaber [312]
Efficiency [-]
Reduction ratio [-]


3.4 kW/kg
0.09 kW/kg
Hobbyist Brushless [784]
Faulhaber DC [122]
Faulhaber BL [41]
Maxon DC [1088]
Maxon BL [155]
Namiki DC [15]
Namiki BL [12]
Portescap DC [24]
Various tiny DC [23]
Maximum continuous power [W]
Mass [kg]


Brushless controllers [170]
38.5 kW/kg ≡ 0.026 kg/kW
Maximum power [W]
Mass [kg]


Hobbyist Brushless [224]
Faulhaber DC [122]
Faulhaber BL [41]
Maxon DC [1088]
Maxon BL [155]
Namiki DC [15]
Namiki BL [12]
Various tiny DC [15]
Maximum efficiency []
Maximum continuous power [W]


5.26 kW/kg ≡ 0.19 kg/kW
1 kW/kg
Maxon [685]
Faulhaber [312]
Maximum continuous power [W]
Mass [kg]

$$m = m_{fixed} + m_{af} + m_{sc} + m_{mppt} + m_{bat} + m_{prop}$$

$$P_{lvl} = \left(\frac{C_D}{C_L^{3/2}}\sqrt{\frac{2A_r g^3}{\rho}}\right)\left(\frac{m^{3/2}}{S}\right)$$

$$m_{fixed} = m_{av} + m_{pld}$$

$$P_{tot} = \frac{1}{\eta_{ctrl}\eta_{mot}\eta_{grb}\eta_{plr}}(P_{lvl}) + \frac{1}{\eta_{BEC}}(P_{av} + P_{pld})$$

$$m_{bat} = \frac{T_{night}}{\eta_{dchrg}\kappa_{bat}} P_{tot}$$

$$m_{mppt} = k_{mppt} 2\eta_{sc}\eta_{cbr}\eta_{mppt\ conv}\eta_{mppt\ algor} I_{max} A_{sc}$$

$$m_{sc} = (\kappa_{sc} + \kappa_{add}) A_{sc}$$

$$A_{sc} = P_{tot}\left(1 + \frac{T_{night}}{T_{day}}\frac{1}{\eta_{chrg}\eta_{dchrg}}\right)\left(\frac{\pi}{2\eta_{sc}\eta_{cbr}\eta_{mppt}\kappa_{wthr} I_{max}}\right)$$

$$P_{tot} = \frac{1}{\eta_{ctrl}\eta_{mot}\eta_{grb}\eta_{plr}}(P_{lvl}) + \frac{1}{\eta_{BEC}}(P_{av} + P_{pld})$$

$$P_{lvl} = \left(\frac{C_D}{C_L^{3/2}}\sqrt{\frac{2A_r g^3}{\rho}}\right)\left(\frac{m^{3/2}}{S}\right)$$

$$A_{sc} = P_{tot}\left(1 + \frac{T_{night}}{T_{day}}\frac{1}{\eta_{chrg}\eta_{dchrg}}\right)\left(\frac{\pi}{2\eta_{sc}\eta_{cbr}\eta_{mppt}\kappa_{wthr} I_{max}}\right)$$

$$m_{fixed} = m_{av} + m_{pld}$$

$$m = m_{fixed} + m_{af} + m_{sc} + m_{mppt} + m_{bat} + m_{prop}$$

$$m_{sc} = (\kappa_{sc} + \kappa_{add}) A_{sc}$$

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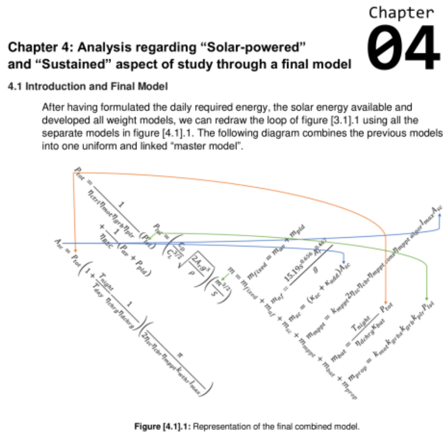
$$m_{bat} = \frac{T_{night}}{\eta_{dchrg}\kappa_{bat}} P_{tot}$$


Chapter 04

Chapter 4: Analysis regarding “Solar-powered” and “Sustained” aspect of study through a final model

4.1 Introduction and Final Model

After having formulated the daily required energy, the solar energy available and developed all weight models, we can redraw the loop of figure [3.1].1 using all the separate models in figure [4.1].1. The following diagram combines the previous models into one uniform and linked “master model”.

Figure [4.1].1: Representation of the final combined model.

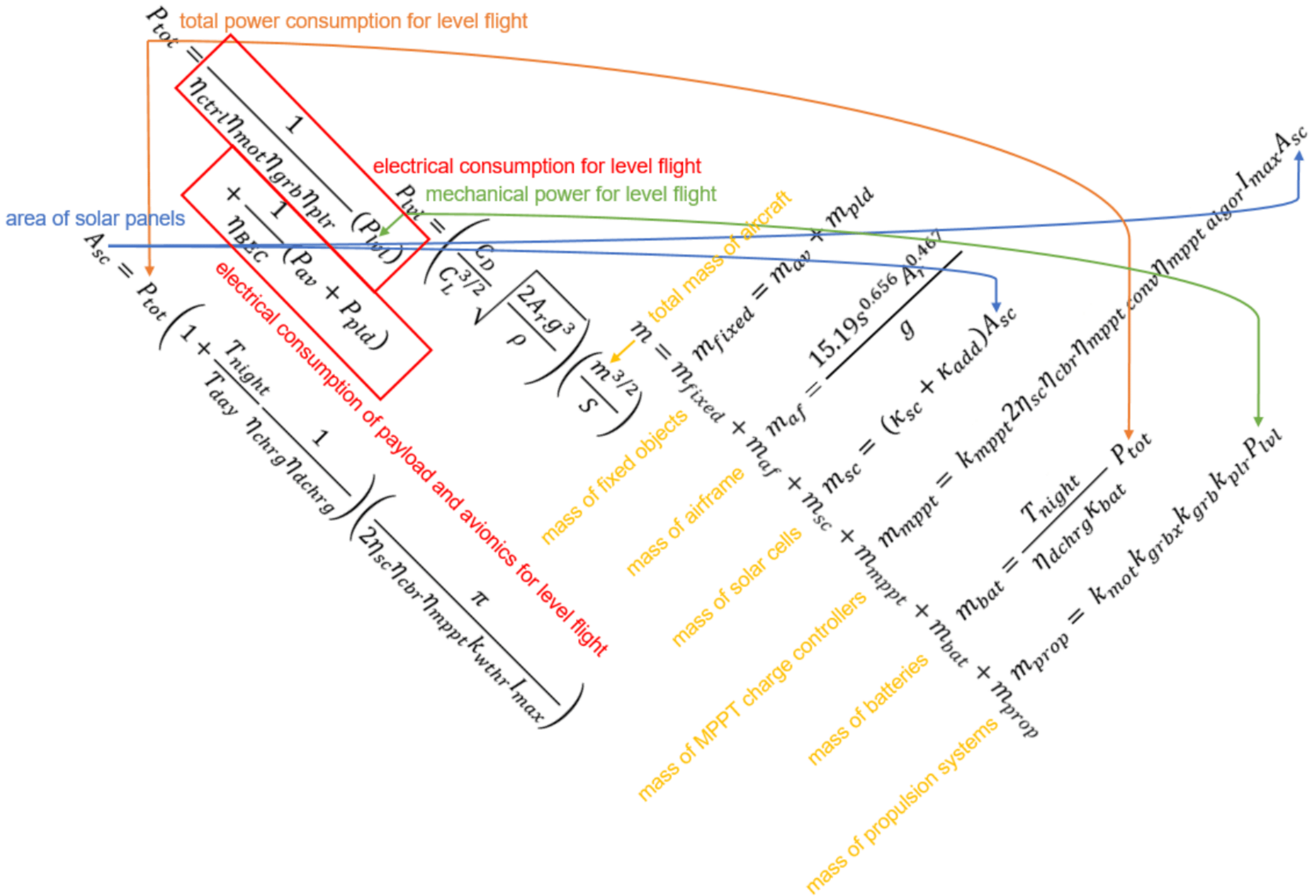


Figure [4.1].2: Representation of the final combined model with labels to further clarify interfacing of the different models in the “master model”.

Chapter 04

Chapter 4: Analysis regarding “Solar-powered” and “Sustained” aspect of study through a final model

4.1 Introduction and Final Model

After having formulated the daily required energy, the solar energy available and developed all weight models, we can redraw the loop of figure [3.1].1 using all the separate models in figure [4.1].1. The following diagram combines the previous models into one uniform and linked “master model”.

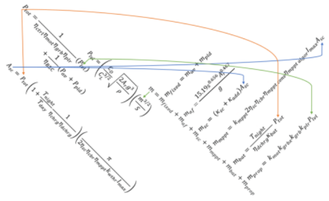


Figure [4.1].1: Representation of the final combined model.

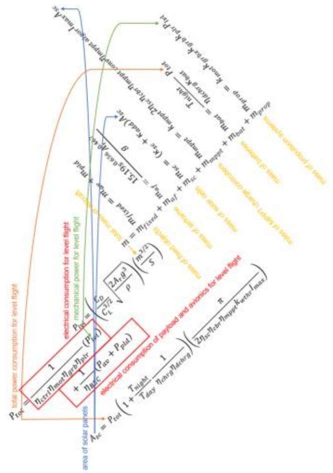


Figure [4.1].2: Representation of the final combined model with labels to further clarify interfacing of the different models in the “master model”.

4.2 Class Separation

In order to be able to extract a conclusive conclusion we must separate the parameters into separate sections to aid calculations:

(1) Parameters linked to real-world technology of today
  a. Efficiencies
  b. Power Consumption
  c. Etc.
(2) Parameters linked to the mission
  a. Air Density
  b. Day duration
  c. Night Duration
  d. Mass of Payload
  e. Power Consumption of Payload
  f. Etc.
(3) Parameters varied by user to obtain range of possible aircraft (if possible) and thus allows for further analysis to determine the feasibility of theoretically infinite flight for a variety of mission use cases. Here, these parameters are variables and vary on the parameters we input in class 1 and class 2, if the values of the class 3 variables lie within the physical constraints of class 3 and our universe then theoretically infinite flight is possible.

Class 1 of Parameters

Variable	Value	Description	Unit	Source
C_L	0.4	Coefficient of Lift		[76][77]
$C_{D\ Aerofoil}$	0.014	Coefficient of Drag		[76][77]
$C_{D\ Parasite}$	0.006	Coefficient of Drag		Table [1.4].1
e_o	0.875	Oswald Efficiency Factor		Table [1.4].1
I_{max}	945	Maximum sun irradiance	[W m^{-2}]	Figure [3.4].3
Ψ_{bat}	220*3600	Gravimetric Energy Density of Battery	[J kg^{-1}]	Figure [2.4].1
κ_{sc}	0.3279	Mass density of solar cells	[kg m^{-2}]	[53]
κ_{add}	0.2850	Mass density of additional mass around solar panels	[kg m^{-2}]	Conservative Estimate
k_{mppt}	0.0004223	Mass to power ratio of MPPT	[kg W^{-1}]	Figure [3.5].1
k_{prop}	0.0007602	Mass to power ratio of Propulsion Systems	[kg W^{-1}]	Table [3.6].1
m_{av}	0.074	Mass of Avionics	[kg]	[78]
η_{BEC}	0.75	Efficiency of step-down converter		[63]
η_{sc}	0.324	Efficiency of solar cells		Figure [2.3].4
η_{cbr}	0.85	Efficiency of curved solar panels		Figure [3.4].4 [72]
η_{chrg}	0.95	Efficiency of battery charge		[64]
η_{dchrg}	0.95	Efficiency of battery discharge		[64]
η_{ctrl}	0.95	Efficiency of motor controller		Table [3.6].2
η_{grb}	0.97	Efficiency of gearbox		Table [3.6].2
η_{mot}	0.85	Efficiency of motor		Table [3.6].2
$\eta_{mppt\ conv}$	0.97	Efficiency of DC to DC converter of MPPT		[64]
$\eta_{mppt\ algor}$	0.98	Efficiency of tracking algorithm of MPPT		[64]
η_{plr}	0.85	Efficiency of propeller		Table [3.6].2
P_{av}	2.5	Power consumed by avionics and autopilot	[W]	[78]
g	9.81	Gravitational constant	[m s^{-2}]	[79]

Table [4.2].1: Class I of Parameters table, data from existing technologies or natural constraints

Class 2 of Parameters

Variable	Value	Description	Unit	Source
m_{pld}	1.015	Mass of the Payload (Cannon Camera)	[kg]	[74]
T_{day}	13.4*3600	Time period of day, time from sunrise to sunset	[s]	[72]
ρ	1.293	Density of air	[kg m^{-3}]	[73]
k_{wthr}	0.7	Arbitrary weather constant		Conservative Estimate
P_{pld}	21	Power consumed by payload (Cannon Camera)	[W]	[75]

Table [4.2].2: Class II of Parameters table, mission specific, in this case carrying a Canon camera for aerial imagery.

Class 3 of Parameters

Variable	Value	Description	Unit
m	17.50	Total mass	[kg]
S	12.40	Wing span	[m]
A_r	19.35	Aspect ratio	

Table [4.2].2: Class III of Parameters table, set by the user.

4.3 Final Model Analysis

Using the parameters from Table [4.1].1, Table [4.2].2, and Table [4.2].3 then using the equation in figure [4.1].2 we are able to obtain:

$$m = m_{fixed} + m_{af} + m_{sc} + m_{mppt} + m_{bat} + m_{prop}$$

$$\Rightarrow m = (m_{av} + m_{pld}) + m_{af} + m_{sc} + m_{mppt} + m_{bat} + m_{prop}$$

$$\Rightarrow m = (m_{av} + m_{pld}) + \frac{15.19 s^{0.656} A_r^{0.467}}{g} + m_{sc} + m_{mppt} + m_{bat} + m_{prop}$$

$$\Rightarrow m = (m_{av} + m_{pld}) + \frac{15.19 s^{0.656} A_r^{0.467}}{g} + (\kappa_{sc} + \kappa_{add})A_{sc} + m_{mppt} + m_{bat} + m_{prop}$$

$$\Rightarrow m = (m_{av} + m_{pld}) + \frac{15.19 s^{0.656} A_r^{0.467}}{g} + (\kappa_{sc} + \kappa_{add})A_{sc} + k_{mppt} 2\eta_{sc}\eta_{cbr}\eta_{mppt\ conv}\eta_{mppt\ algor} I_{max} A_{sc} + m_{bat} + m_{prop}$$

$$\Rightarrow m = (m_{av} + m_{pld}) + \frac{15.19 s^{0.656} A_r^{0.467}}{g} + (\kappa_{sc} + \kappa_{add})A_{sc} + k_{mppt} 2\eta_{sc}\eta_{cbr}\eta_{mppt\ conv}\eta_{mppt\ algor} I_{max} A_{sc} + \frac{T_{night}\, P_{tot}}{\eta_{dchrg}\Psi_{bat}} + m_{prop}$$

$$\Rightarrow m = (m_{av} + m_{pld}) + \frac{15.19 s^{0.656} A_r^{0.467}}{g} + (\kappa_{sc} + \kappa_{add})A_{sc} + k_{mppt} 2\eta_{sc}\eta_{cbr}\eta_{mppt\ conv}\eta_{mppt\ algor} I_{max} A_{sc} + \frac{T_{night}\, P_{tot}}{\eta_{dchrg}\Psi_{bat}} + k_{mot}k_{grb}k_{ctrl}k_{plr}P_{lvl}$$

$$\Rightarrow m = (m_{av} + m_{pld}) + \frac{15.19 s^{0.656} A_r^{0.467}}{g} + (\kappa_{sc} + \kappa_{add})A_{sc} + k_{mppt} 2\eta_{sc}\eta_{cbr}\eta_{mppt} I_{max} A_{sc} + \frac{T_{night}\, P_{tot}}{\eta_{dchrg}\Psi_{bat}} + k_{prop}P_{lvl}$$

$$\Rightarrow m = ((0.074) + (1.015)) + \frac{15.19 s^{0.656} A_r^{0.467}}{(9.81)} + ((0.3279) + (0.2850))A_{sc} + (0.0004223)(2)(0.324)(0.85)(945)A_{sc} + \frac{((24 - 13.4) * 3600)P_{tot}}{(0.95)(220 * 3600)} + (0.0007602)P_{lvl}$$

$$\Rightarrow m = (1.089) + (1.5484)s^{0.656}A_r^{0.467} + (0.6129)A_{sc} + (0.2198)A_{sc} + (0.5072)P_{tot} + (0.0007602)P_{lvl}$$

$$\Rightarrow m = (1.089) + (1.5484)s^{0.656}A_r^{0.467} + (0.8327)A_{sc} + (0.5072)P_{tot} + (0.0007602)P_{lvl}$$

$$\Rightarrow m = (1.089) + (1.5484)(12.40)^{0.656}19.35^{0.467} + (0.8327)A_{sc} + (0.5072)P_{tot} + (0.0007602)P_{lvl}$$

$$\Rightarrow m = 33.3032 + (0.8327)A_{sc} + (0.5072)P_{tot} + (0.0007602)P_{lvl}$$

Equation [4.3].0

$$P_{lvl} = \left(\frac{C_D}{C_L^{3/2}}\sqrt{\frac{2A_r g^3}{\rho}}\right)\left(\frac{m^{3/2}}{S}\right)$$

$$\Rightarrow P_{lvl} = \left(\frac{(C_{D\ Aerofoil} + C_{D\ Parasite})}{C_L^{3/2}}\sqrt{\frac{2A_r g^3}{\rho}}\right)\left(\frac{m^{3/2}}{S}\right)$$

$$\Rightarrow P_{lvl} = \left(\frac{((0.014) + (0.006))}{(0.40)^{3/2}}\sqrt{\frac{2(19.35)(9.81)^3}{(1.293)}}\right)\left(\frac{m^{3/2}}{(12.40)}\right)$$

$$\Rightarrow P_{lvl} = (0.107296)m^{3/2}$$

Equation [4.].0

$$P_{tot} = \frac{1}{\eta_{ctrl}\eta_{mot}\eta_{grb}\eta_{plr}}(P_{lvl}) + \frac{1}{\eta_{BEC}}(P_{av} + P_{pld})$$

$$\Rightarrow P_{tot} = \frac{1}{(0.95)(0.85)(0.97)(0.85)}(P_{lvl}) + \frac{1}{(0.75)}(21)(2.5)$$

$$\Rightarrow P_{tot} = (1.5020)(P_{lvl}) + 140$$

Equation [4.3].0

$$A_{sc} = P_{tot}\left(1 + \frac{T_{night}}{T_{day}}\frac{1}{\eta_{chrg}\eta_{dchrg}}\right)\left(\frac{\pi}{2\eta_{sc}\eta_{cbr}\eta_{mppt}k_{wthr}I_{max}}\right)$$

$$\Rightarrow A_{sc} = P_{tot}\left(1 + \frac{((24 - 13.4) * 3600)}{(13.4 * 3600)}\frac{1}{(0.95)(0.95)}\right)\left(\frac{\pi}{2(0.324)(0.85)(0.7)(945)}\right)$$

$$\Rightarrow A_{sc} = P_{tot}(0.01659975)$$

Equation [4.3].04

Solving the equations equation [4.3].01, equation [4.3].02, equation [4.3].03, and equation [4.3].04 yields:

$$A_{sc} = 6.56983256\ meters^2$$

Comparing this to the input value of:

$$A_r = \frac{S^2}{A_w}$$

$$\Rightarrow A_w = \frac{S^2}{A_r}$$

Equation [1.4].06

$$\Rightarrow A_w = \frac{(12.40)^2}{(19.35)}$$

$$\Rightarrow A_w = 7.94625323\ meters^2$$

$$A_{sc} < A_w$$

$$\Rightarrow 6.56983256\ meters^2 < 7.94625323\ meters^2$$

The area of the solar panels is less that than that of the area of the wings, thus fitting within the physical constraints of reality and our universe which therefore means that *given the current technology of today (that is used to determine the parameters) continuous and theoretically infinite flight is possible.*

Chapter

05

Chapter 5: Conclusion of Study

5.1 Conclusions

Continuous and theoretically infinite solar flight in UAVs feasible in the sense that it is:

(1) Physically possible as the physical constraints of the universe and the laws of the first principles physics are obeyed.
(2) Practically viable in the current day in the sense that it uses current data from existing technologies.
(3) Relatively economically viable in the sense no research-grade solar cells, batteries, materials are used to determine the Class I parameters.

5.2 Looking Ahead

To build further upon this study the following can be completed:

(1) Use more data to hand validate the master model created here and perhaps extend on the model's simplification in aspects by creating a more true-to-life model by reducing simplifications
(2) Use MATLAB® [80] or R programming language [81] to:
    a. Plot and calculate more accurate lines of best fit gradient values
    b. Program master model and surround smaller models so that they can be engaged and disengaged from each other so that the characteristic of the mathematical model can be determined
    c. Programming the model on a computer allows for a large range of data to be in input in Class III allowing:
        i. Plotting parameters of all feasible aircraft with today's technology
        ii. Determining the next best course action of technological development to make continuous solar flight easier and with greater energetic margins
(3) Determine why, if continuous solar flight is possible, there is no widespread use of this technology

Solving the equations equation [4.3].01, equation [4.3].02, equation [4.3].03, and equation [4.3].04 yields:

$$A_{sc} = 6.56983256\ meters^2$$

Comparing this to the input value of:

$$A_r = \frac{S^2}{A_w}$$

$$\Rightarrow \quad A_w = \frac{S^2}{A_r} \qquad \text{Equation [1.4].06}$$

$$\Rightarrow \quad A_w = \frac{(12.40)^2}{(19.35)}$$

$$\Rightarrow \quad A_w = 7.94625323\ meters^2$$

$$A_{sc} < A_w$$

$$\Rightarrow \quad 6.56983256\ meters^2 < 7.94625323\ meters^2$$

The area of the solar panels is less that than that of the area of the wings, thus fitting within the physical constraints of reality and our universe which therefore means that *given the current technology of today (that is used to determine the parameters) continuous and theoretically infinite flight is possible.*

The Autonomous Focus

01	Contents
02	Title Analysis
03	The Why behind this EPQ
04	The Methodology to Answer the Question Posed by this EPQ
05	Schools of Focus
06	Are the Schools of Focus Connected?
07	The Solar-powered Focus
08	The Sustained Focus
09	Forming the Model
10	The Autonomous Focus
11	Conclusions
12	So why aren't we seeing this right now?
13	Project Management
14	Motivations
15	Looking Back
16	Looking Ahead

Storm and high winds prediction and avoidance.

Hot air updrafts and cold air downdrafts riding.

Altitude planning and course planning to increase solar efficiency.

Conclusions

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Solar-powered flight is feasible and has been done before at low-costs and complexity.

Given the current technology today, continuous and theoretically infinite flight is possible at this very moment.

Autonomous flight is entirely possible as commercial grade solutions already exist and algorithms for meteorological avoidance whilst not open-source are available. Machine learning is also on the rise.

So why aren’t we seeing this right now?

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- Lack of specific constraints set in designs.
- Lack of commercial viability.
- Lack of incentive to switch due to existing aviation industry.
- Scalability.

Project Management

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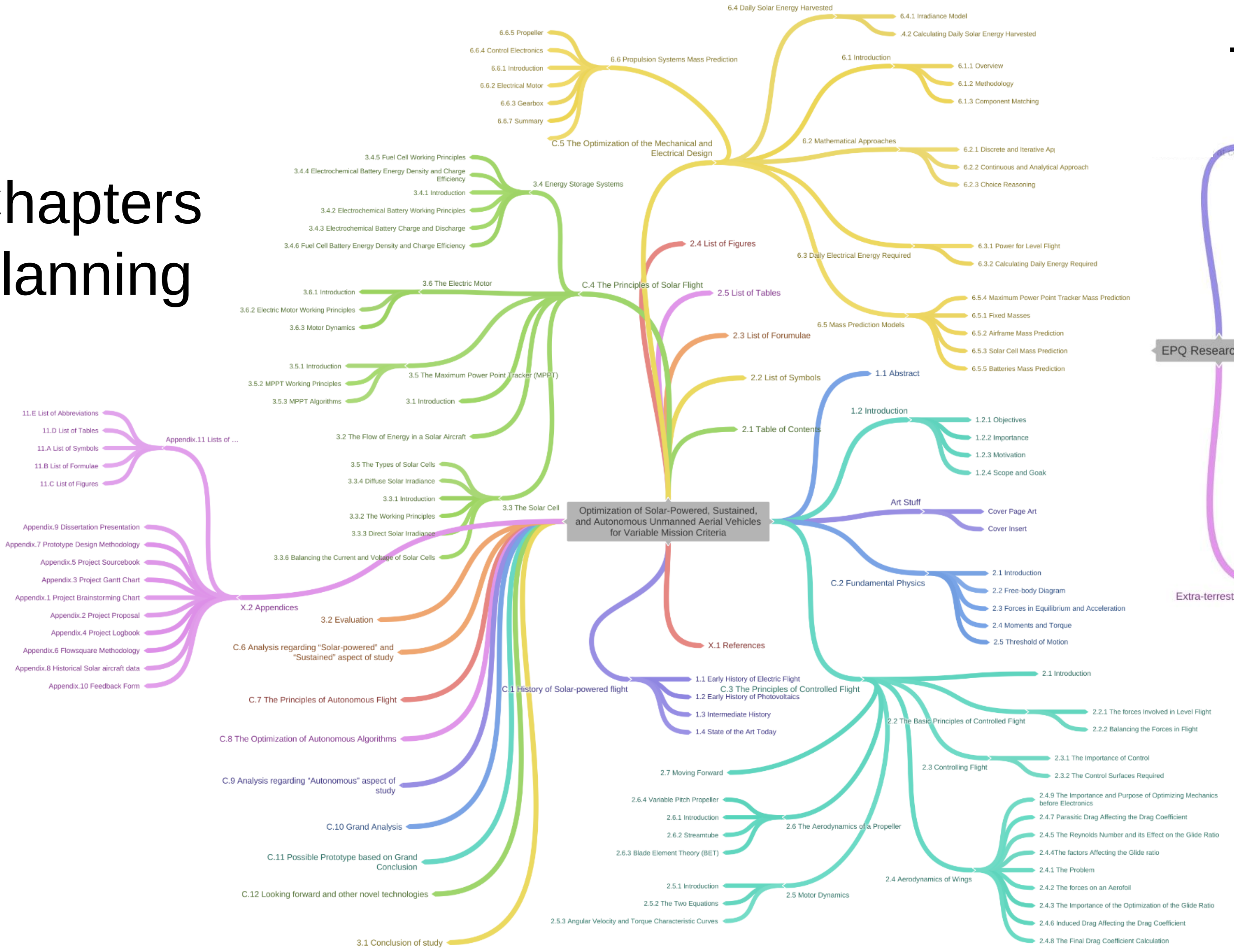
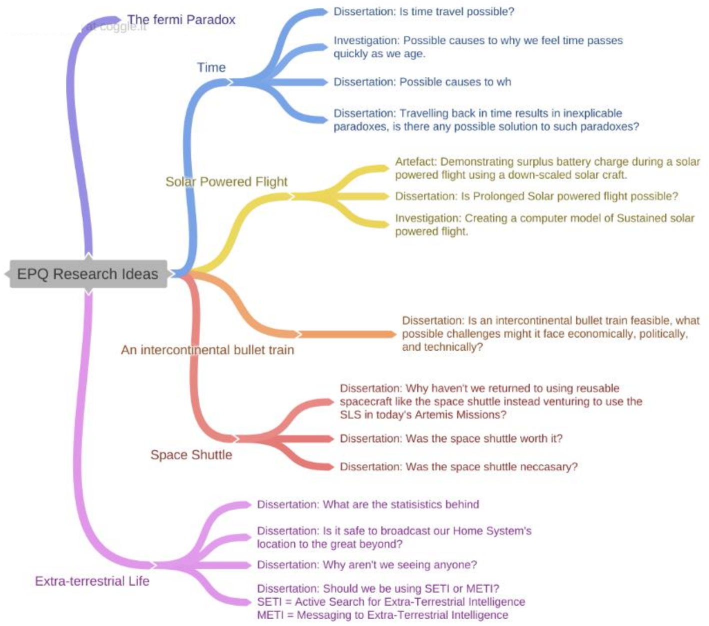
Chapters Planning



Title Planning



Section Three: Activities and timescales

Activities to be carried out during the project:	How long this will take:
(1) Initial planning	2 Weeks
a. Brainstorm EPQ choices and settle for one EPQ project	
b. Brainstorm possible titles and settle on a “working title”	
(2) Project planning	1 Week
a. Find existing research papers for gathering information on existing craft and data	
b. Prepare Gantt chart for overall structure of project delivery	
c. Submit Project proposal form	
(3) Research	6 Weeks
a. Gather information on existing aircraft for brief history	
b. Gather information on the working principles of solar flight and general flight	
(4) Write-up of objectives (3), (4), (5), (6), and (7)	3 Weeks
(5) Carry out objectives (8), (9), and (10)	8 Weeks
(6) Write-up of objectives (8), (9), (10), (11), and (12)	3 Weeks
(7) Write-up objectives (1), (2), (13), and (14)	2 Weeks
(8) Editing	1 week
(9) Presentation	2 Week
a. Produce the presentation	
b. Prepare for oral presentation	
c. Carry-out oral presentation	28 Weeks ← Total Time

(1) Milestone: Finish Filling in project proposal
Target date (set by tutor assessor): 30th January

(2) Milestone: Finish Mid Project review
Target date (set by tutor-assessor): 17th April

(3) Milestone: Finish First draft of project
Target date (set by tutor-assessor): 1st September

(4) Milestone: Final Project submission
Target date (set by tutor-assessor): 1st November

(5) Milestone: Final Oral Presentation
Target date (set by tutor-assessor): Approx. End of November

(6) Milestone: All Paperwork Submission
Target date (set by tutor-assessor): 10th December

Project objectives:

The main object of such a dissertation is to:

(1) Provide an abstract detailing the promise of how solar flight could revolutionize the industry of search and rescue, agriculture, military surveillance, weather prediction, photography, etc.
(2) Provide an introduction to my motivations behind such a project.

(3) Provide a brief overview / account of previous solar flight and accompanying relevant data.
(4) Provide analysis on what has been done so far in the world of solar flight, compare craft, analyse strengths and deficiencies of said craft.
(5) Provide a summary of the basic principles behind solar based flight, and flight in general:
   a. Principles of controlled flight
   b. Principles of solar flight
      i. How power delivery works during the day and during the night (Solar Panel → Charge Controller → Batteries → etc.)
      ii. Metrological factors that must be considered with lightweight aircraft (Such as updrafts, wind, low temperatures, cloudy days, etc.)
   c. Principles of Solar Panels
   d. Principles of Batteries
   e. Principles of RC flight
(6) Provide the challenges faced that prevent prolonged solar flight. (The below is a rough preliminary outline of what majors factors prevent said flight)
   a. Airframe constraints (Aerodynamics, weightiness, flexibility, etc.)
   b. Energy constraints (Batteries, Solar Panels, Battery Charge Controllers, Accompanying flight electronics)
   c. Metrological constraints (High winds, cold/hot air updrafts/downdrafts)
(7) Provide possible solutions to said challenges
(8) Provide a mathematical model that addresses such constraints using available data from previous studies
(9) Provide a fluid model in Flowsquare that verifies such models
(10) Provide a prototype design in Fusion 360 that addresses such challenges
(11) Provide an evaluation of said design
(12) Provide a short overview of emerging technologies that may perhaps aid addressing the aforementioned challenges.

(13) Provide Data evaluation of the data used to build the aforementioned mathematical model.
(14) Provide Source evaluation of sources used in this project

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Stuff to do, *Stuff to be done*, *Stuff to be done concurrently*

- *Draw missing diagrams*
- *Double check all sources cited properly*
- *Add proper evidence to the yellow sections of text*
- *Update Project Logbook*
- *Update Project Sourcebook*
- *Add stuff to all the different lists*

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The promise of solving world-problems.

The proximity to my chosen field of studies.

Continuation of Practical Sustainability.

Looking back

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Greater appreciation and knowledge of continuous mathematical models.

Finding the answer to a multi-faceted complex question from start to finish.

Fitting this in with school-work is tricky.

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12 So why aren’t we seeing this right now?

13 Project Management
14 Motivations

15 Looking Back
16 Looking Ahead

Optimization of Solar-Powered, Sustained, and Autonomous Unmanned Aerial Vehicles for Variable Mission Criteria

Feasibility analysis using Mathematical optimization of solar-powered aircraft using first principles for different mission cases.

further discussions and questions?

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